Recent Results on Open Heavy Flavor at the LHC

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Heavy Flavor Workshop

RHIC& AGS Annual User's Meeting

Brookhaven National Laboratory

20 June, 2017

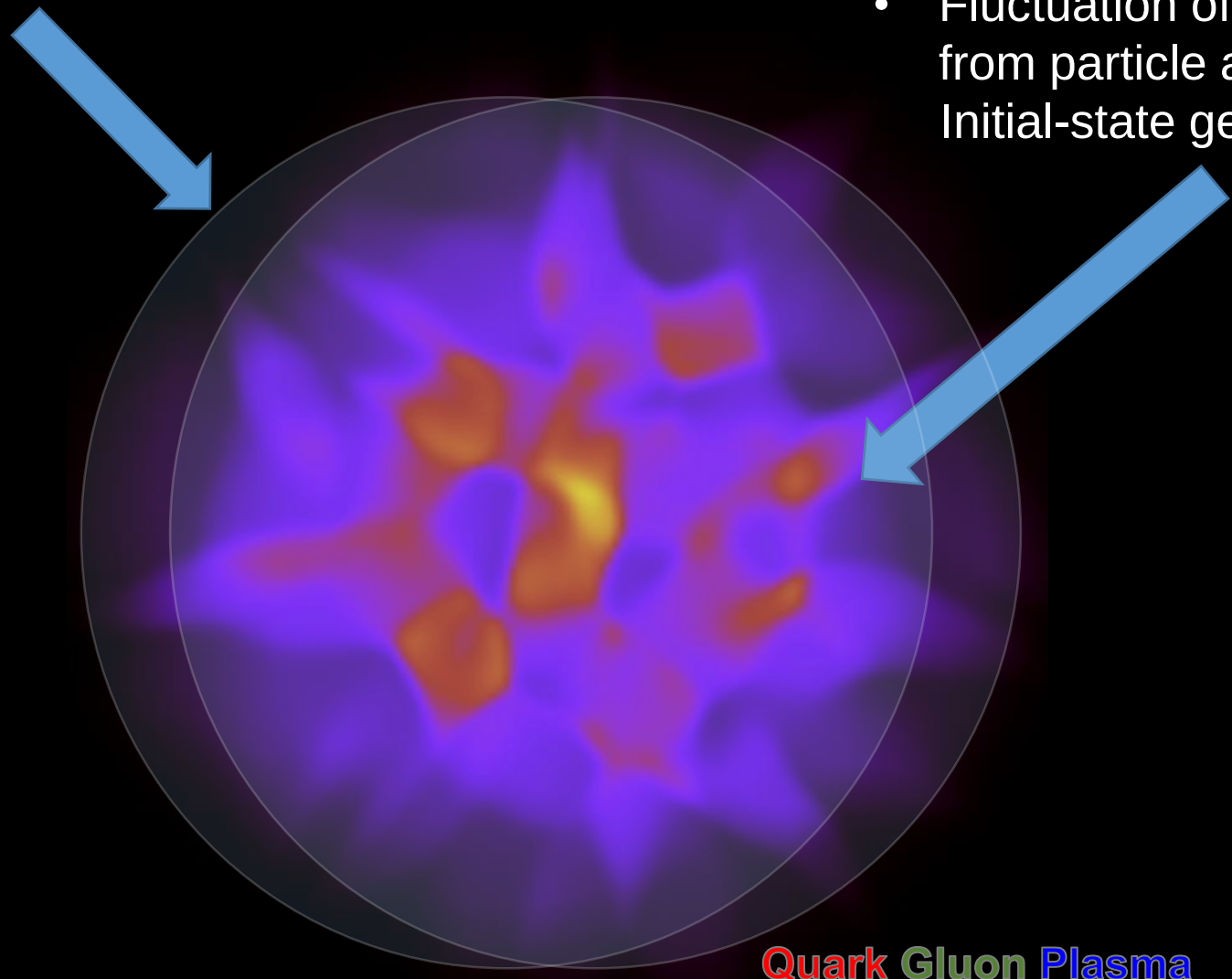
Prepare the Quark Soup

Particle Multiplicity

- Collision impact parameter of the ions
- Energy density of the medium

Azimuthal anisotropy

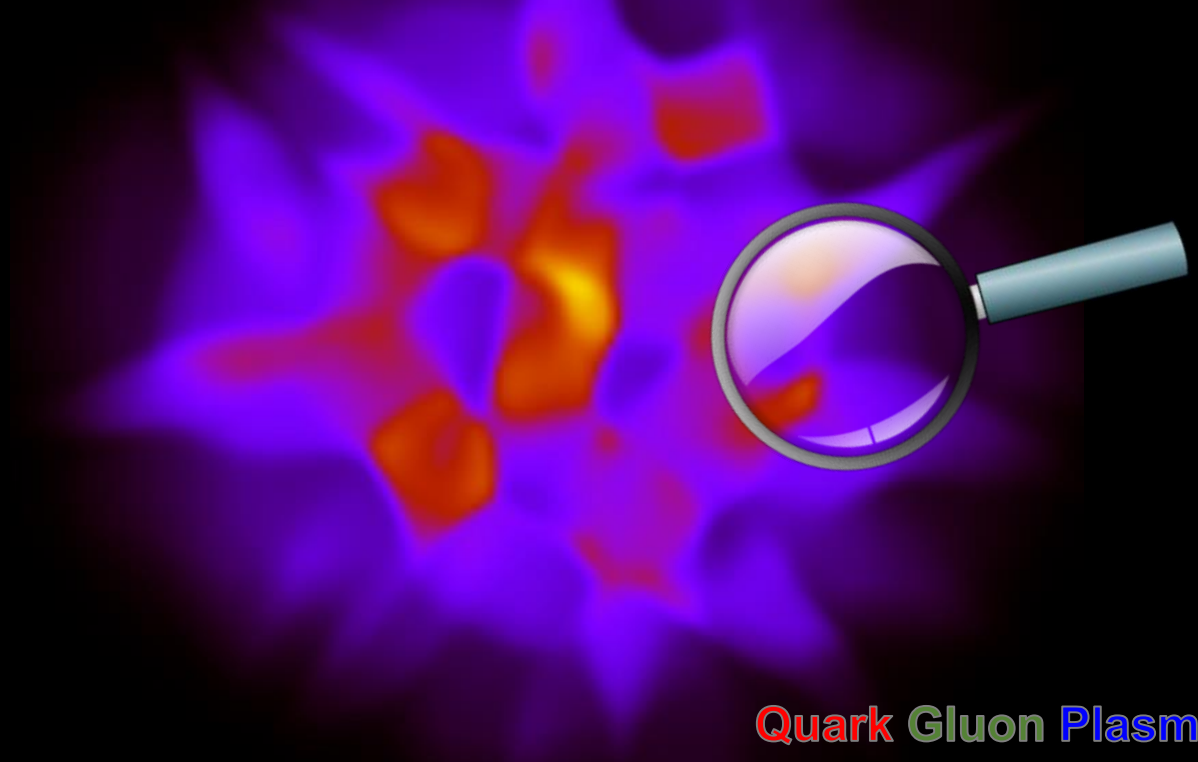
- Early thermalization <1 fm/c
- Shear viscosity
- Fluctuation of v_N coefficients from particle azimuthal correlation: Initial-state geometry fluctuation



Beyond the Analysis of Debris

- How does the strongly interacting medium emerge from an asymptotic free theory (QCD)?

- Can we see quasi particles (quarks and gluons) in the Quark Gluon Plasma ?



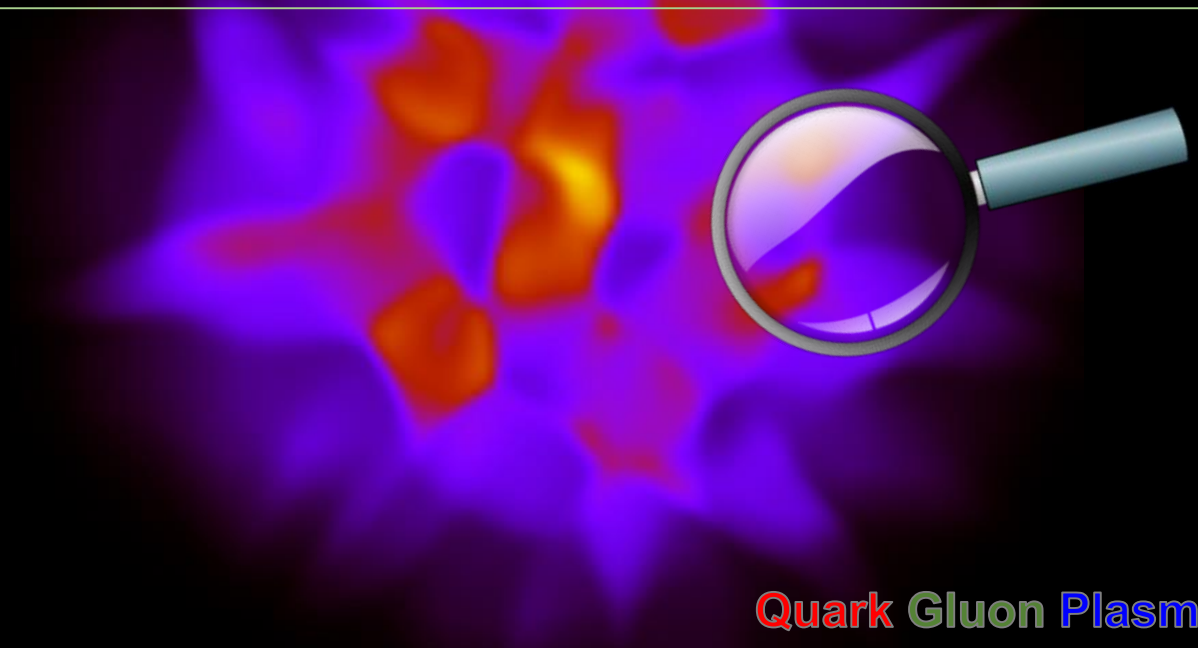
Beyond the Analysis of Debris

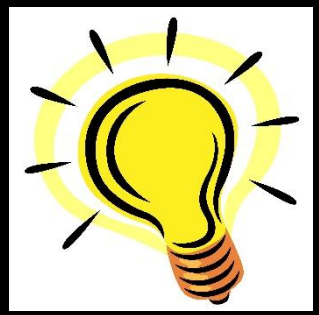
- How does the strongly interacting medium emerge from an asymptotic free theory (QCD)?

Start from "un-thermalized" objects and see how they are thermalized in the Quark Soup

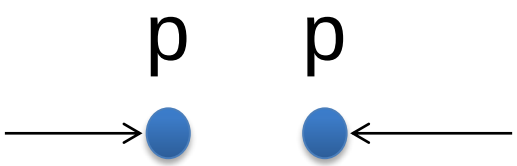
- Can we see quasi particles (quarks and gluons) in the Quark Gluon Plasma ?

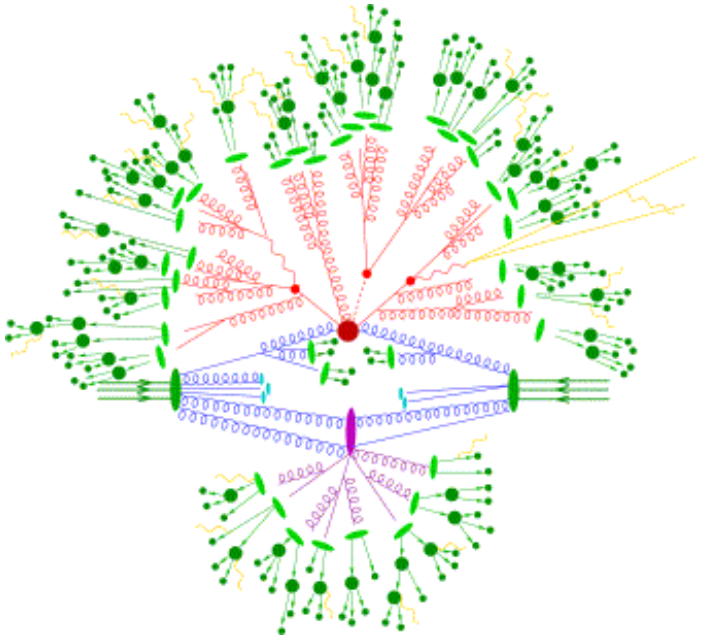
Shoot colored objects through the QGP

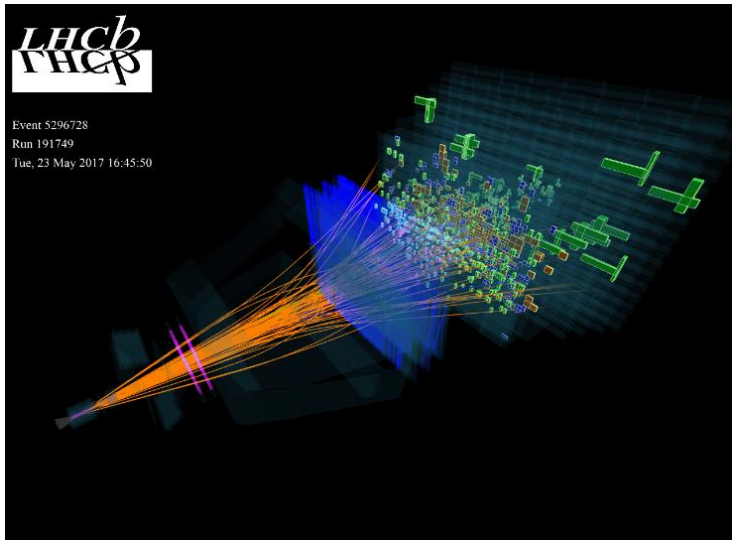




Open Heavy Flavor in pp collisions





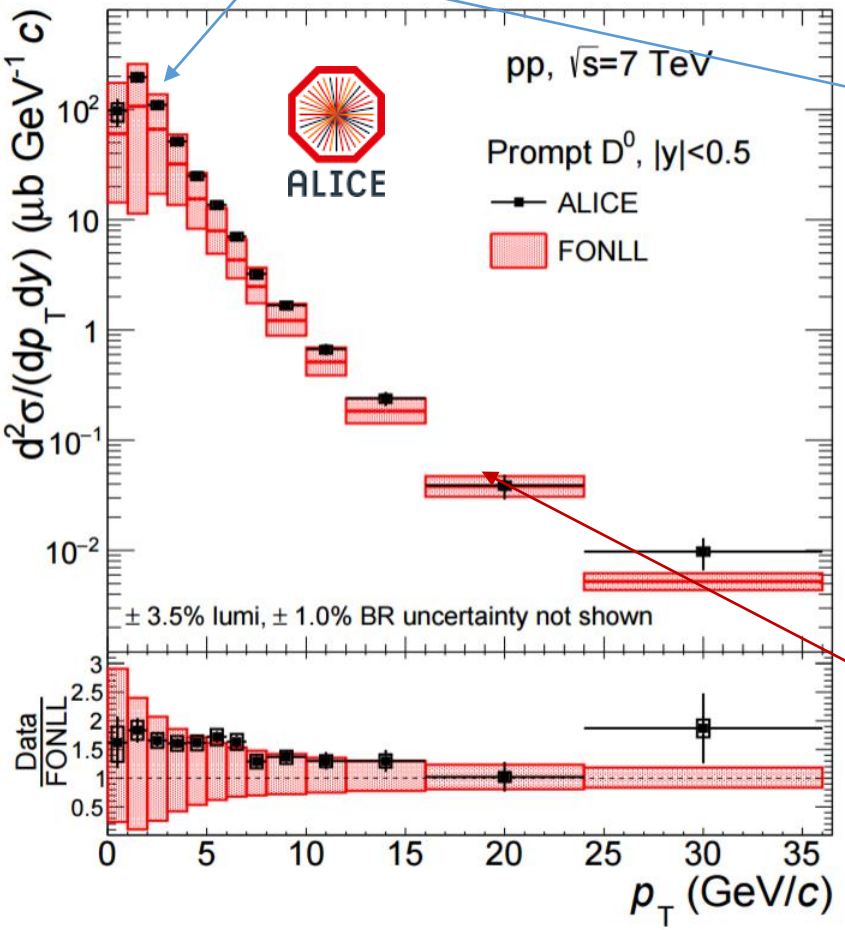


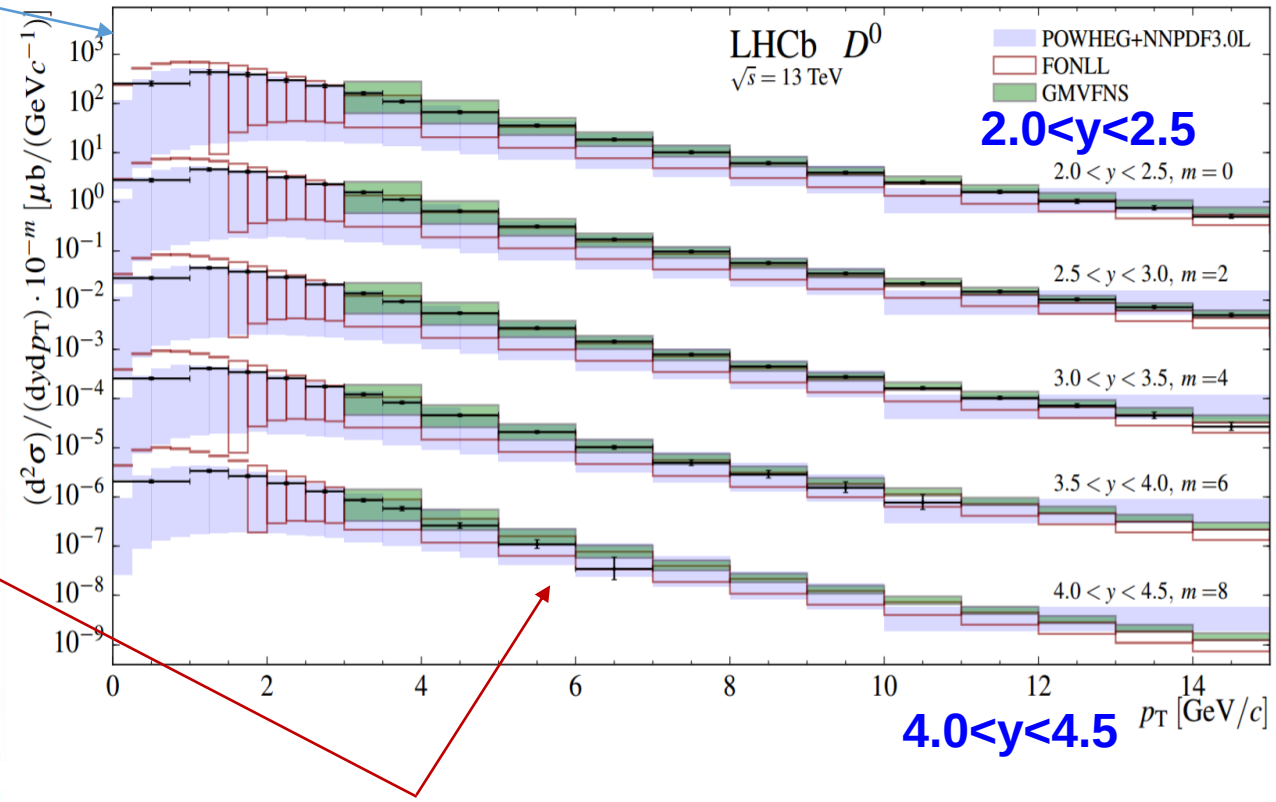
- Important test for QCD: FONLL, GMVFNS …
- Constrain proton parton distribution function
- Baseline for pA and AA collisions

D^0 p_T Spectra in pp at Low p_T

- At very low p_T (<3 GeV):
  data sit in the FONLL uncertainty band

JHEP 1603 (2016) 159
Erratum: JHEP 1705 (2017) 074





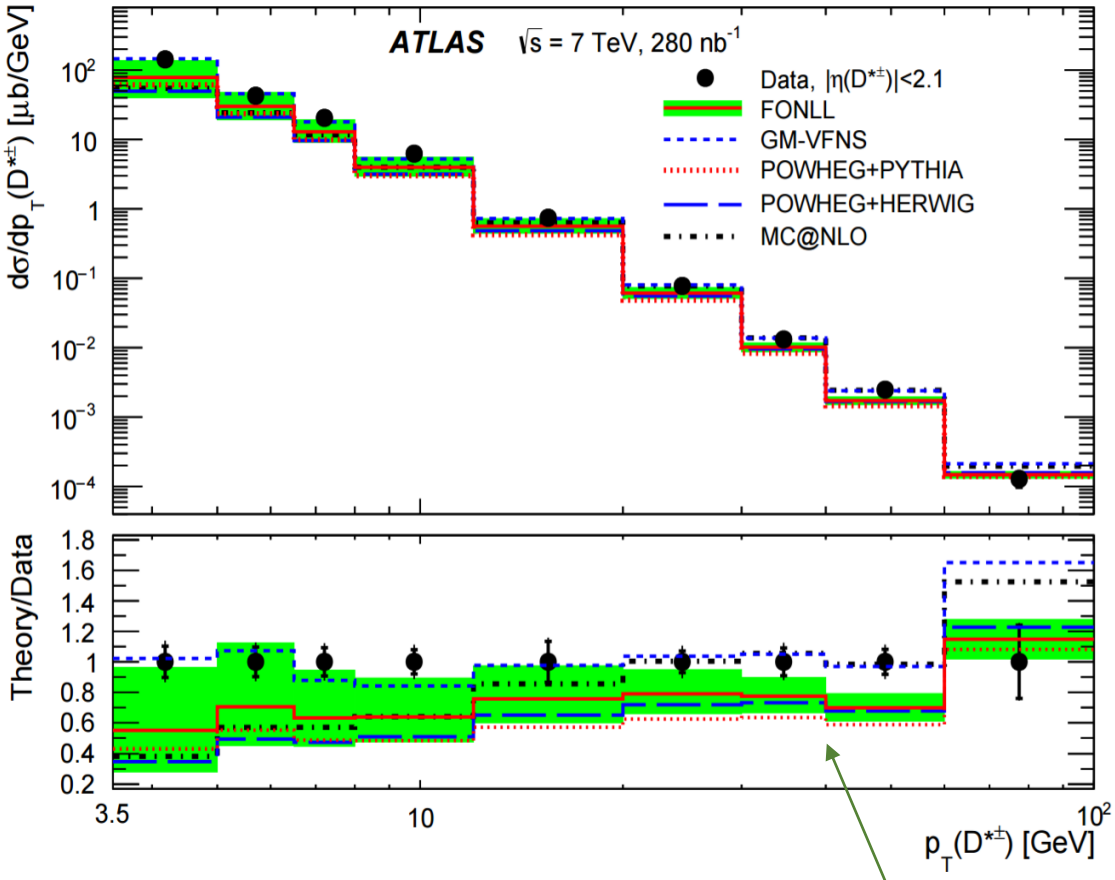
arXiv: 1702.00766
Submitted to EPJC

- At intermediate p_T (>3 GeV),
  data sit at the upper edge of FONLL band

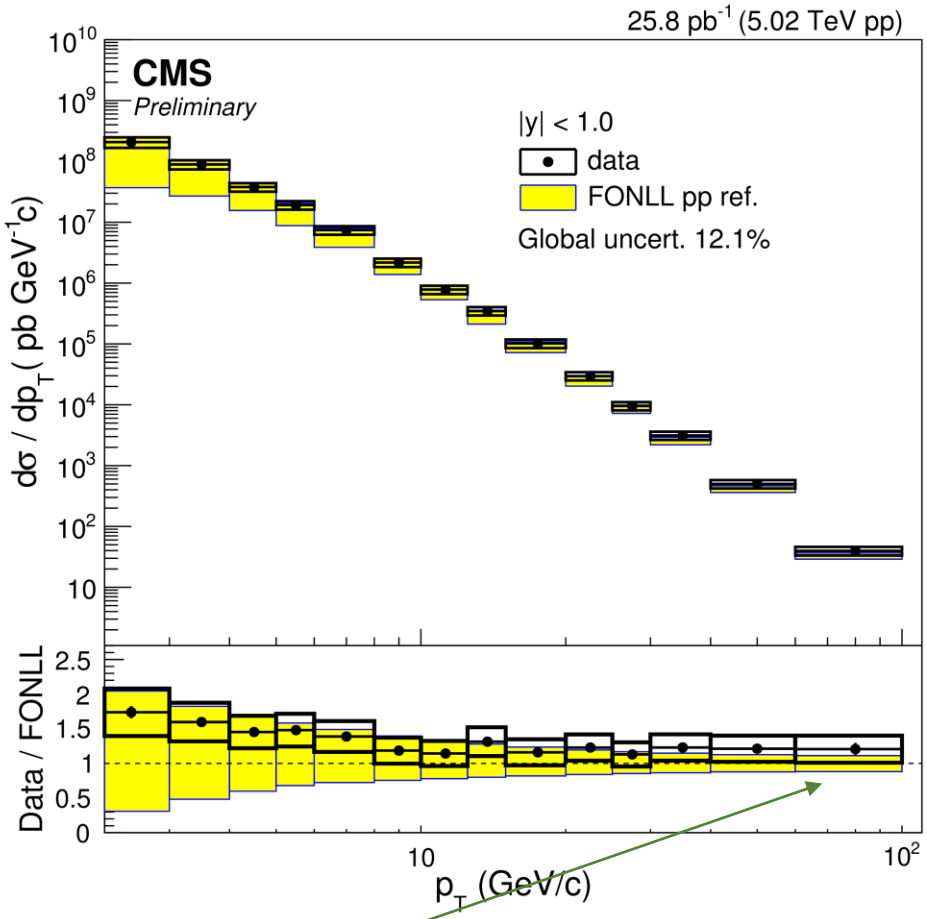
- LHCb data could be used to constrain proton gluon parton density functions in $x<10^{-4}$
(The uncertainty in pp exceeding 30% at Q=1.4 GeV (charm mass))

D* and D^0 p_T Spectra in pp at High p_T

NPB 907 (2016) 717



CMS-PAS-HIN-16-001



- Good agreement with GM-VFNS

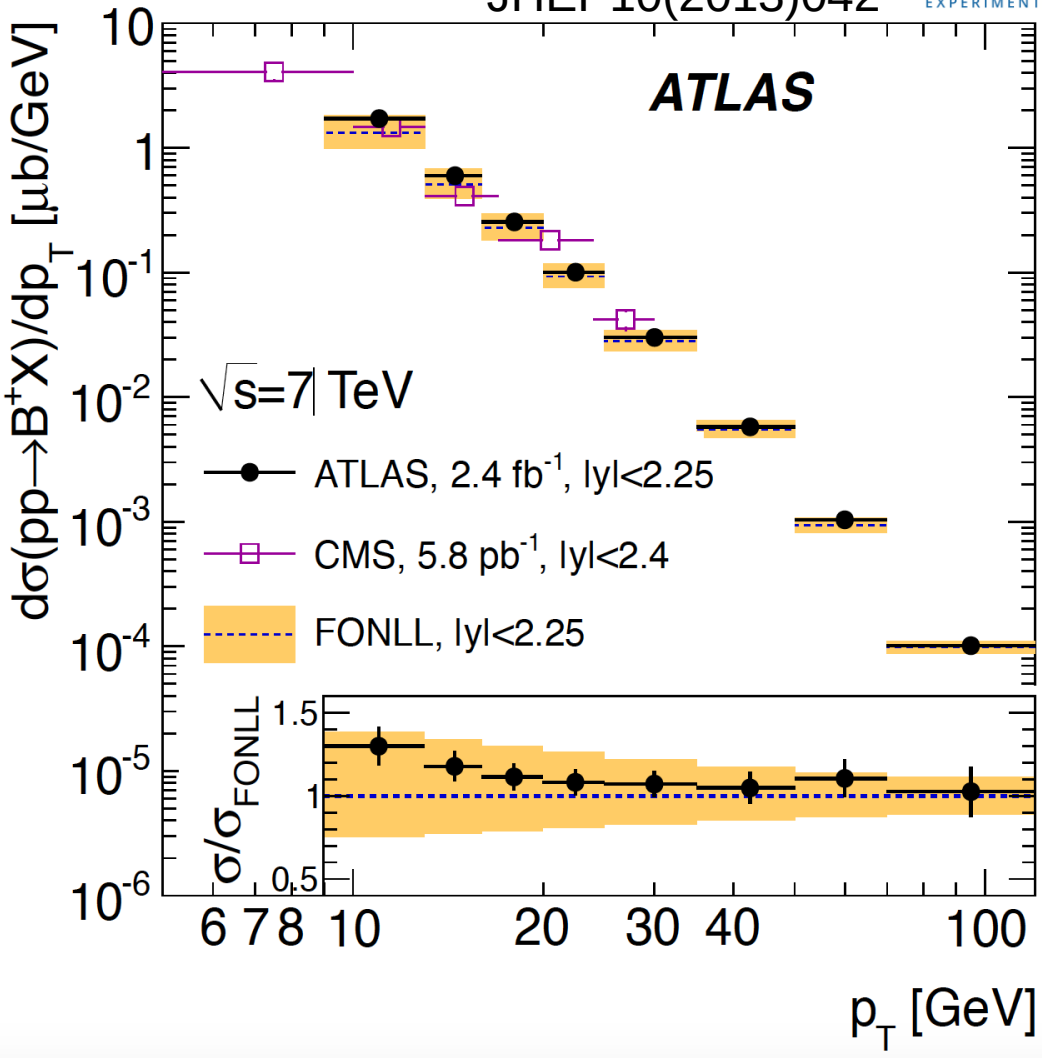
pp at 5.02 TeV

- At high p_T (>20 GeV): data sit at the upper edge of FONLL band or slightly higher than FONLL

B^+ p_T Spectra in pp

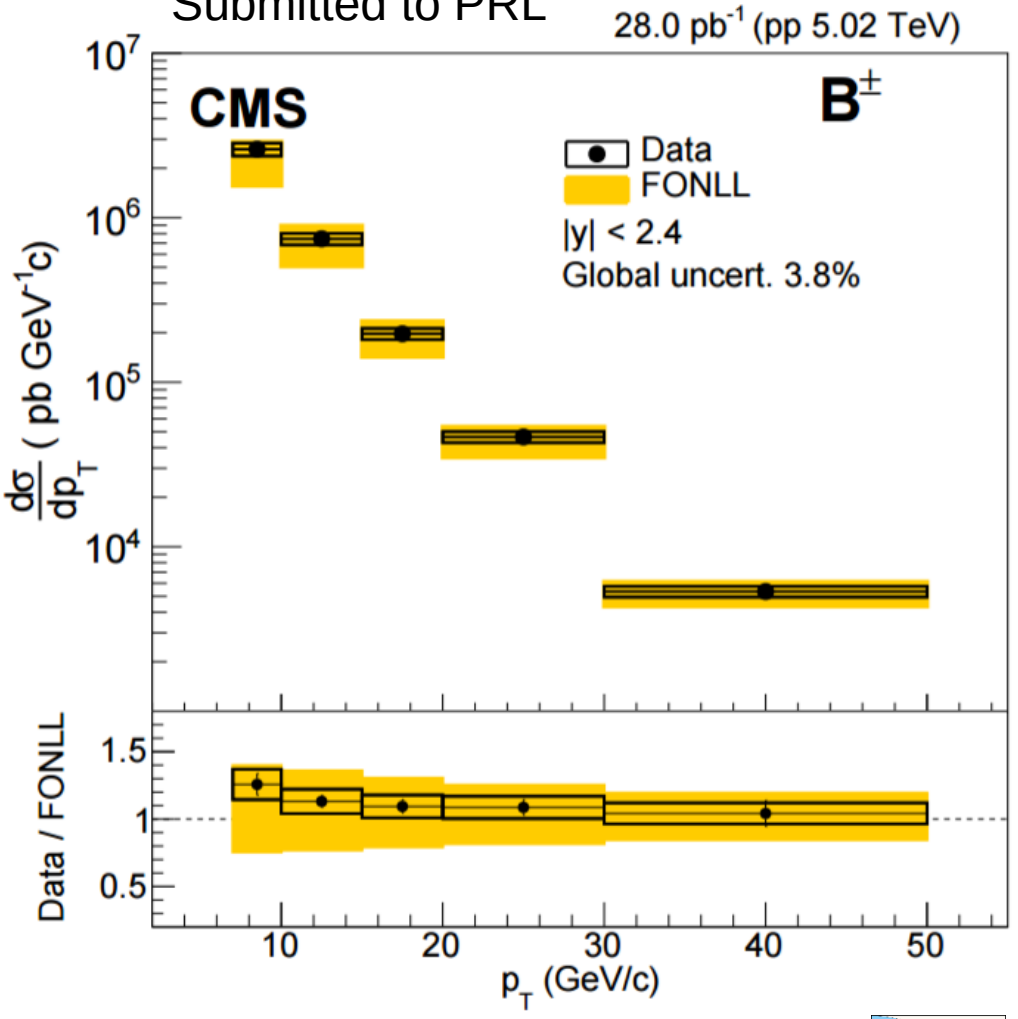
ATLAS B^+ at 7 TeV, |y|<2.25

JHEP10(2013)042



arXiv: 1705.04727

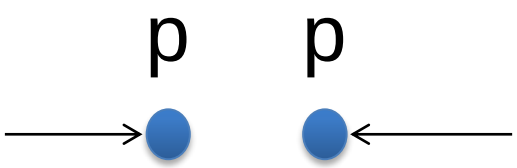
Submitted to PRL

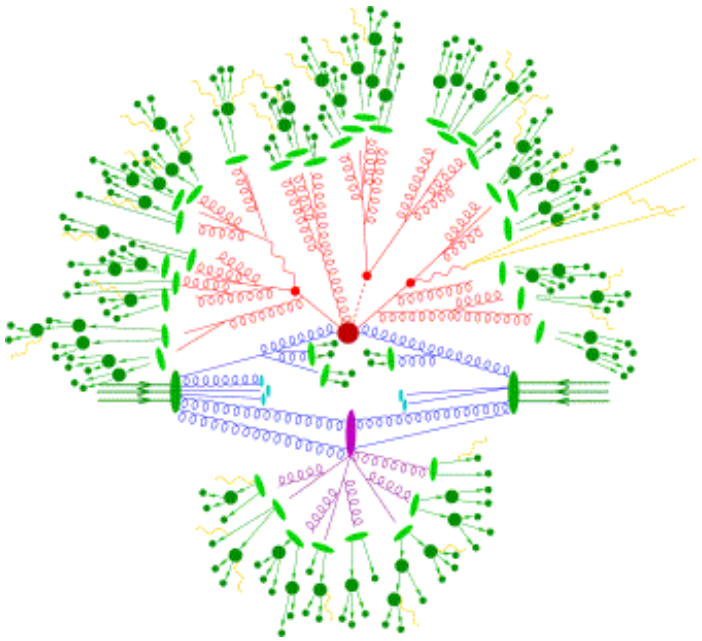


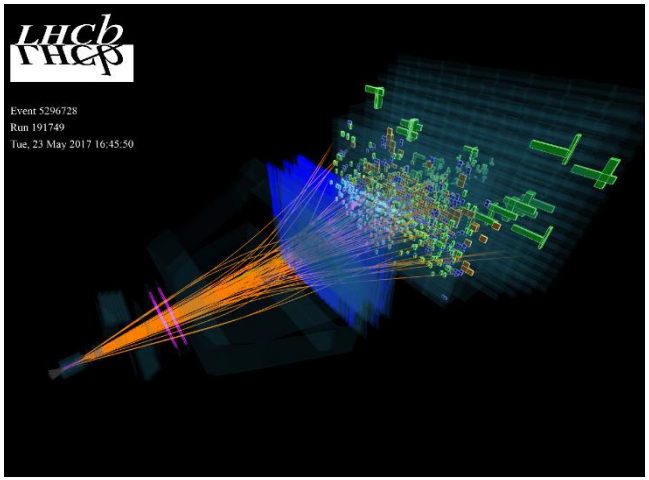
pp at 5.02 TeV

- B^+ spectra in both collision energies described by FONLL

Open Heavy Flavor in pp collisions

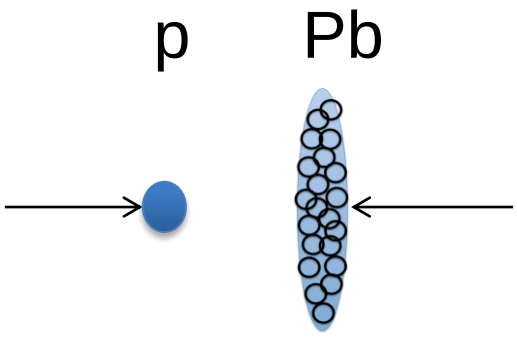


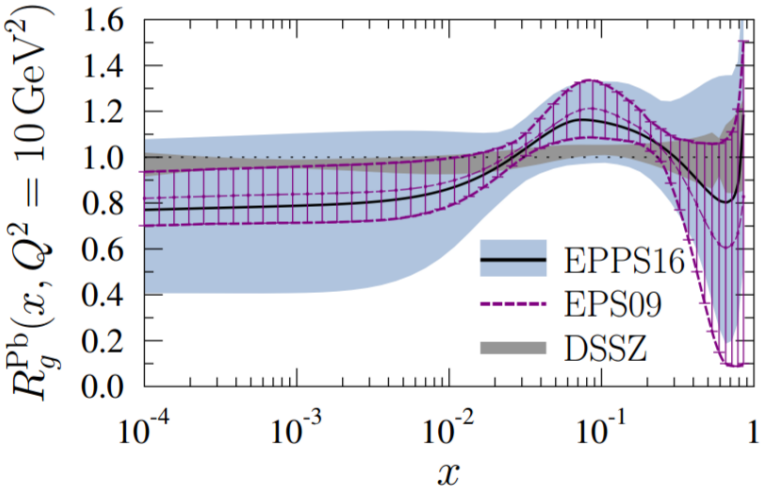


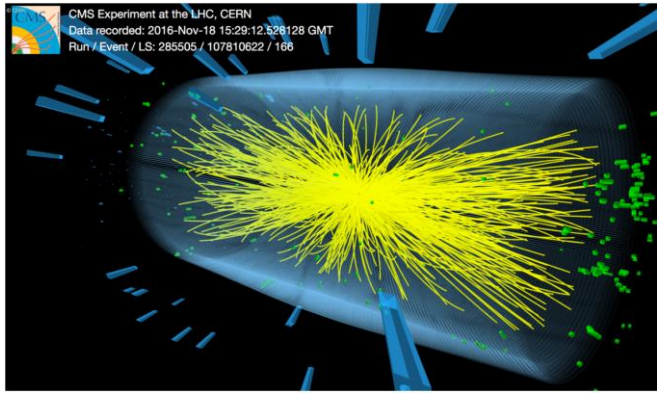


- Important test for QCD: FONLL, GMVFNS …
  - Reasonable description of the LHC data
- Constrain proton parton distribution function
  - High precision LHCb data: constrain low x gluon PDF
- Baseline for pA and AA collisions
  - pp reference at the same collision energy as pPb and PbPb collisions become available

Open Heavy Flavor in pPb

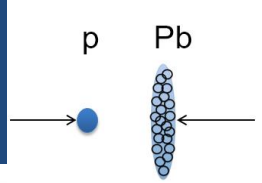




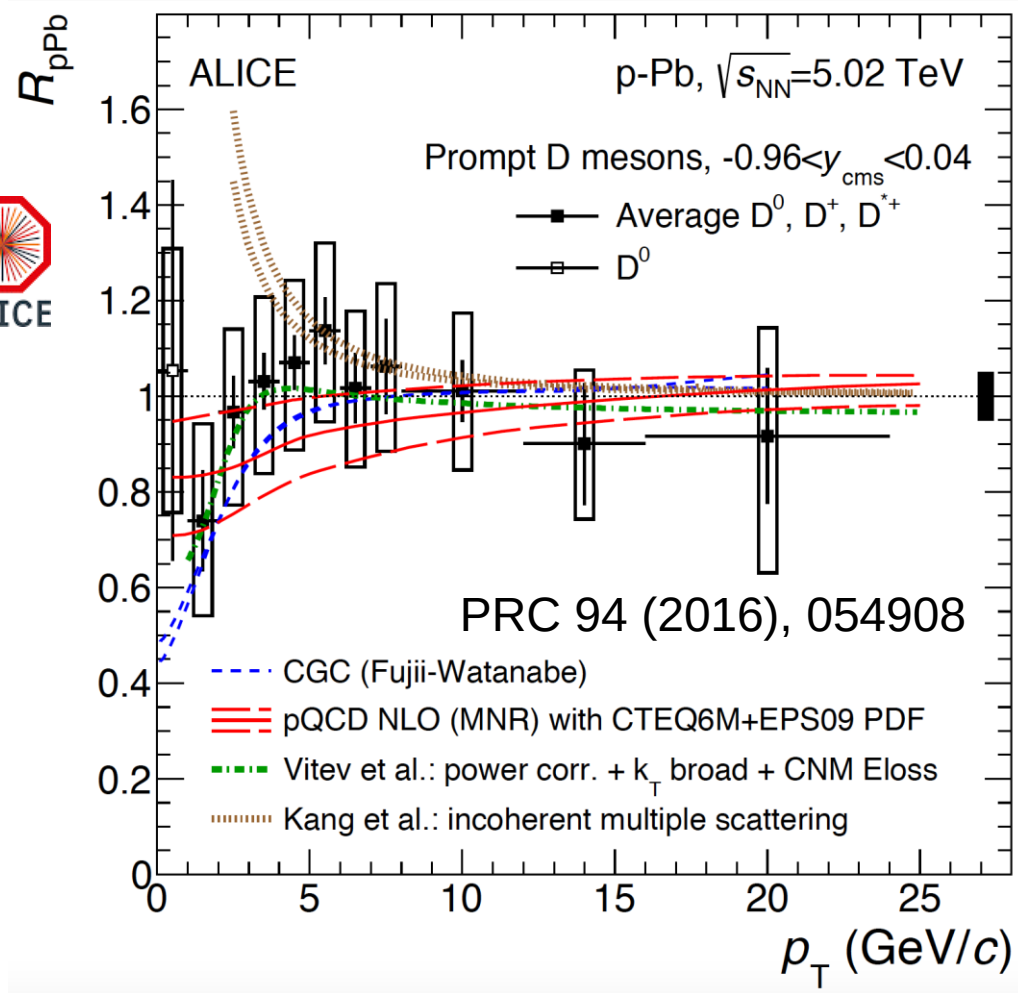


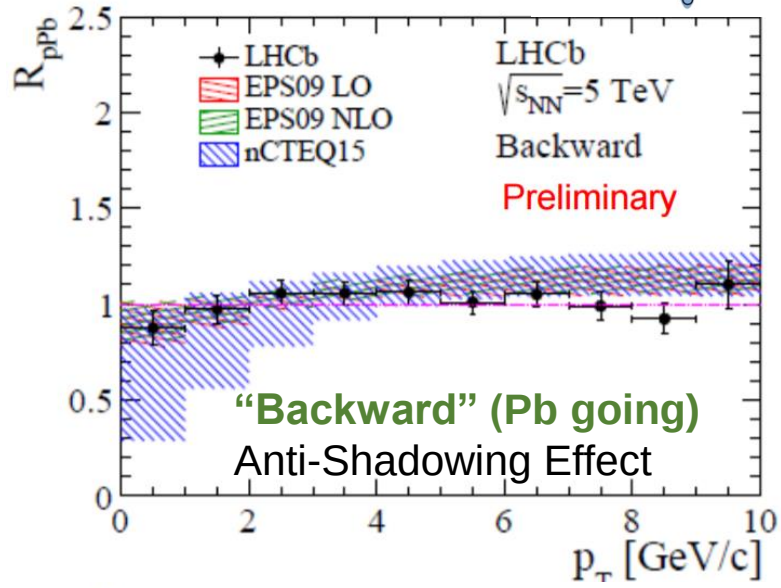
- Test nPDF universality assumption
- Constrain nPDF and test of the gluon saturation models
- Other cold nuclear effects such as E_{loss}, multiple scattering

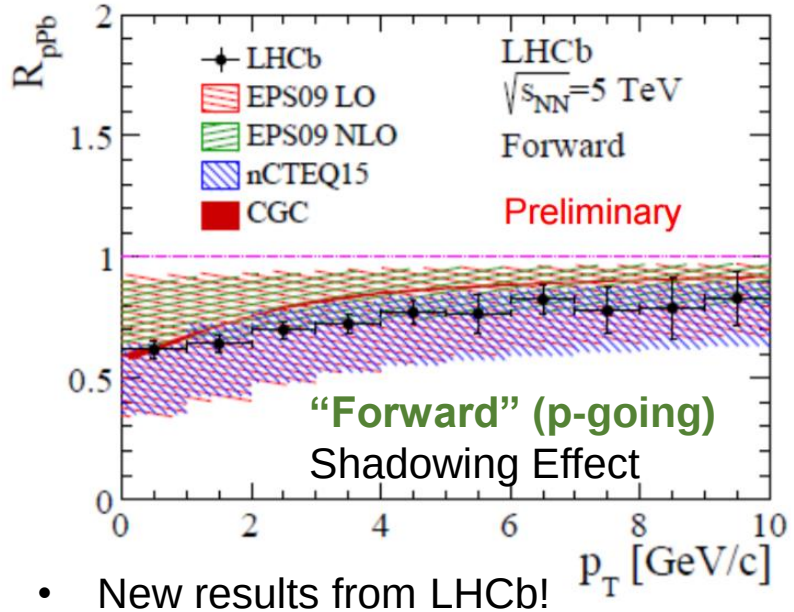
D^0 R_{pPb} at 5.02 TeV



ALICE D R_{pPb} at 5.02 TeV, |y|<0.5





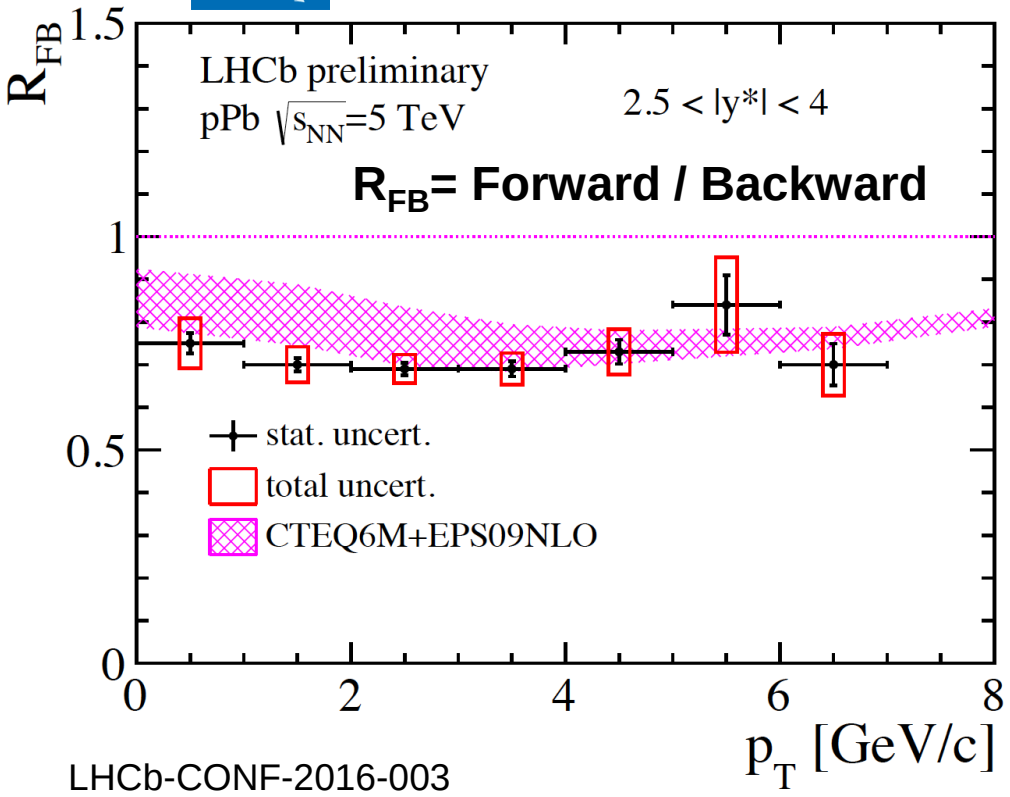


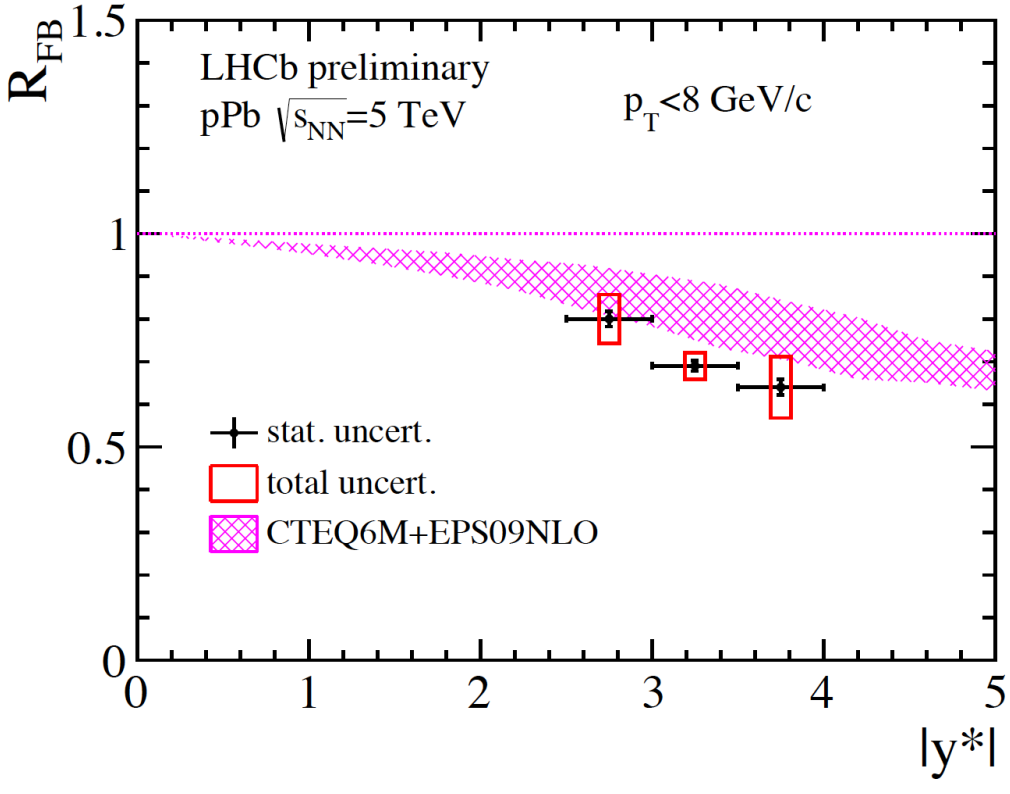
- ALICE R_{pA} data are consistent with 1 within the quoted uncertainty: No Sizable Modification in pPb
- Need to improve the accuracy by **a factor of 3-5** to be able to separate different models

- New results from LHCb!
- High precision RpPb which could contribute to the understanding of the gluon PDF

D^0 meson R_{FB} at 5.02 TeV

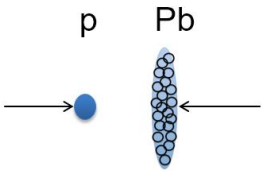
LHCb D^0 forward (F, shadowing) and backward (B, anti-shadowing) ratio as a function of p_T and rapidity





LHCb-CONF-2016-003

- LHCb D^0 R_{FB} : deviate from 1 significantly
- Consistent with NLO calculations that include EPS09 nuclear PDF **(at the edge)**



D^0 meson R_{FB} at 5.02 TeV

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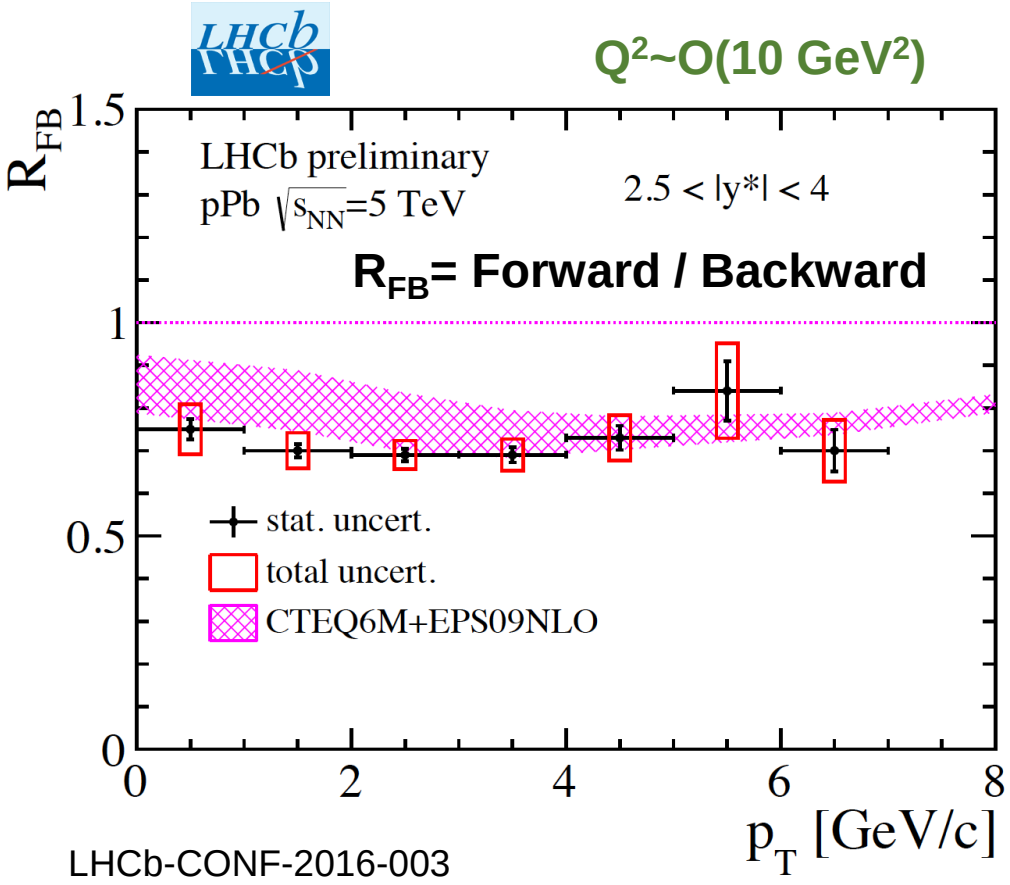
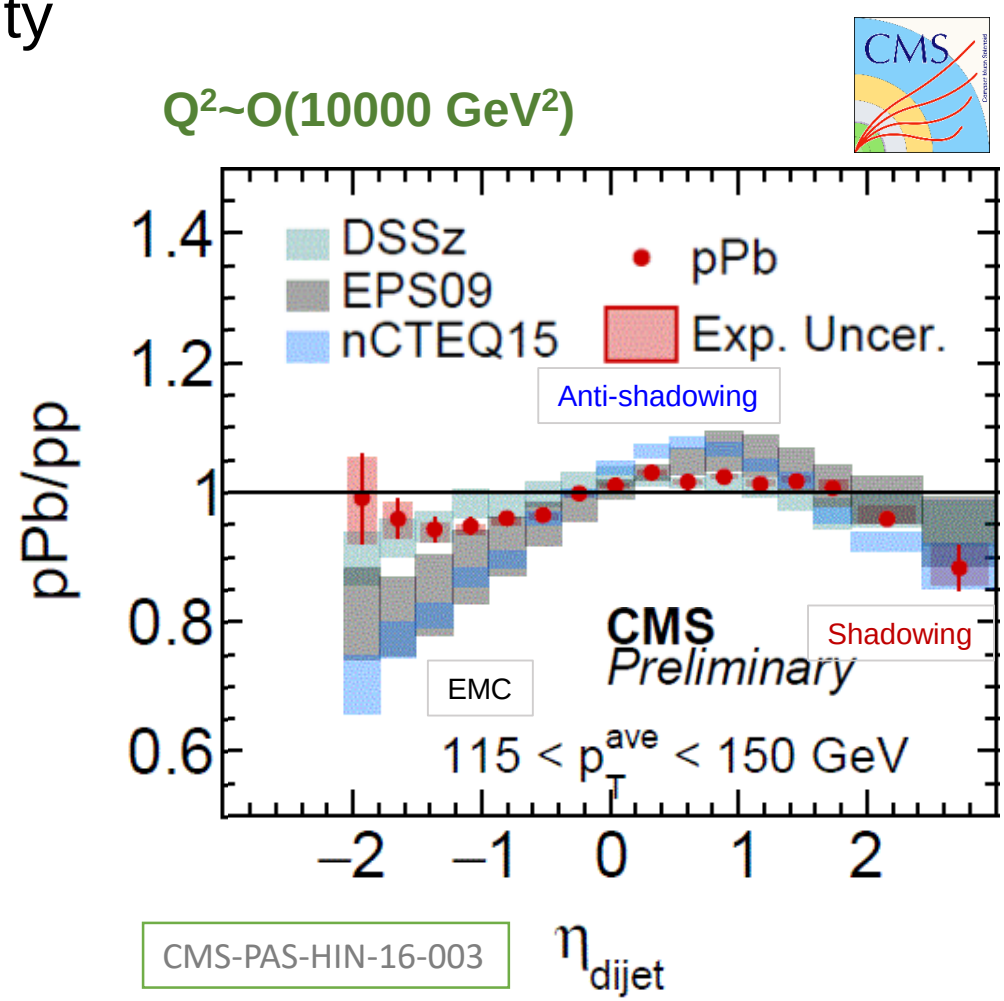
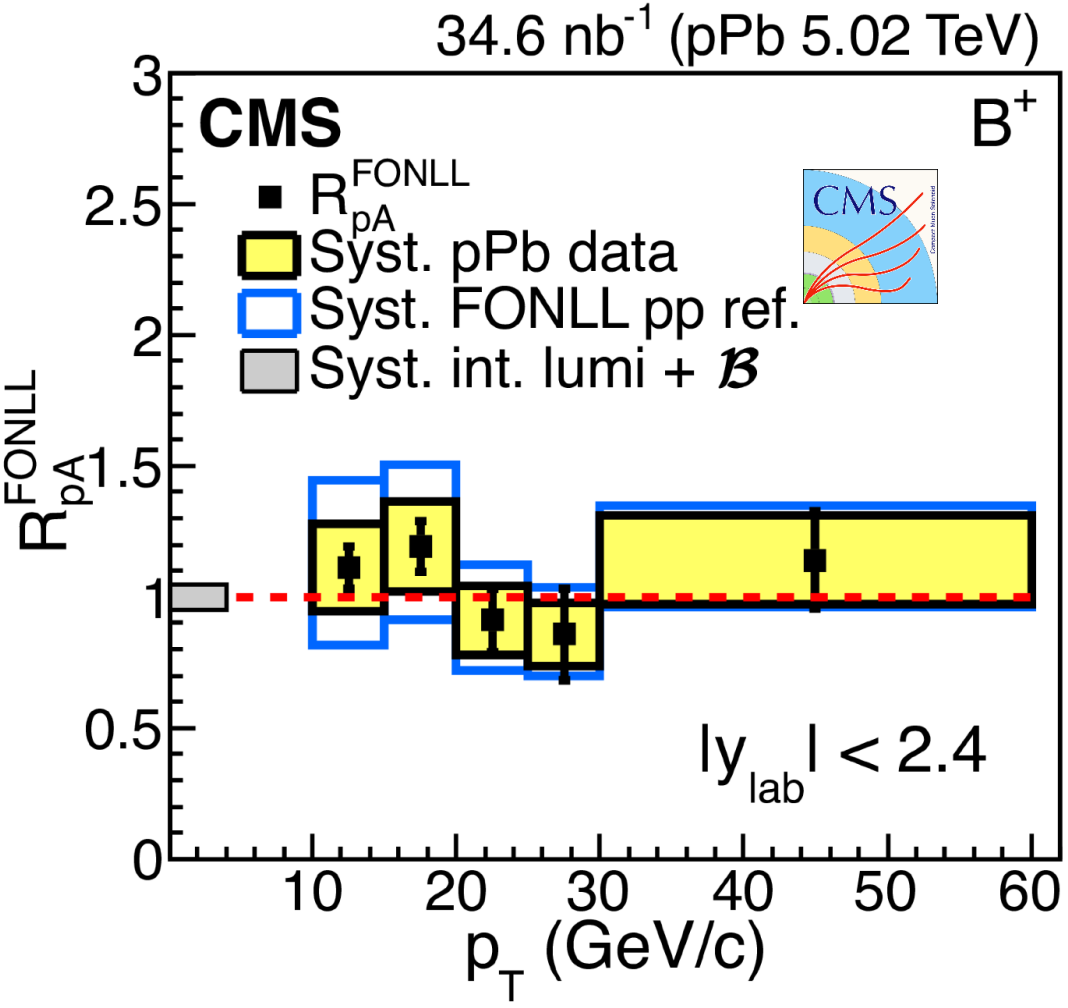




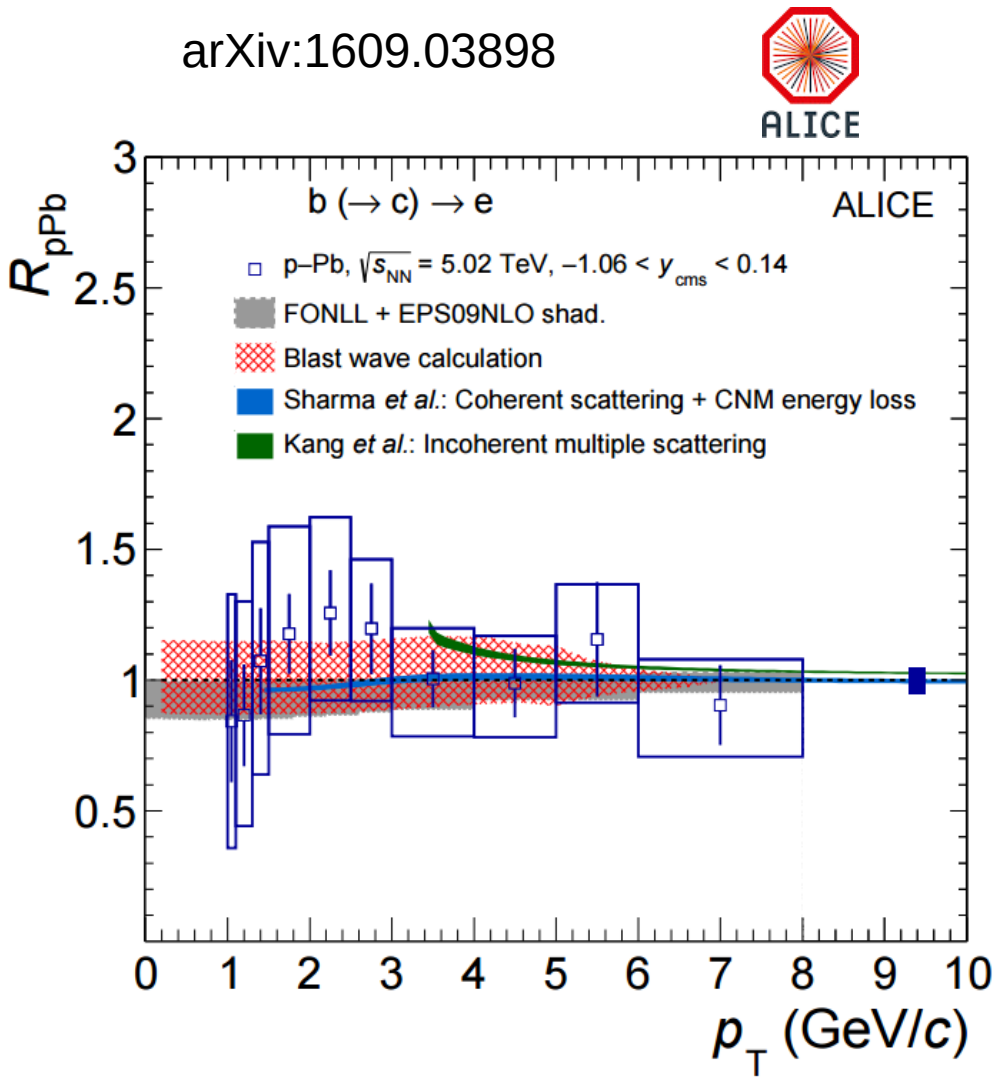
- LHCb D^0 R_{FB} : deviate from 1 significantly
- Consistent with NLO calculations that include EPS09 nuclear PDF **(at the edge)** ↔ Similar to the observation from CMS dijet analysis in pPb

B^+ and b→e R_{pPb} at 5.02 TeV

PRL 116 (2016) 032301



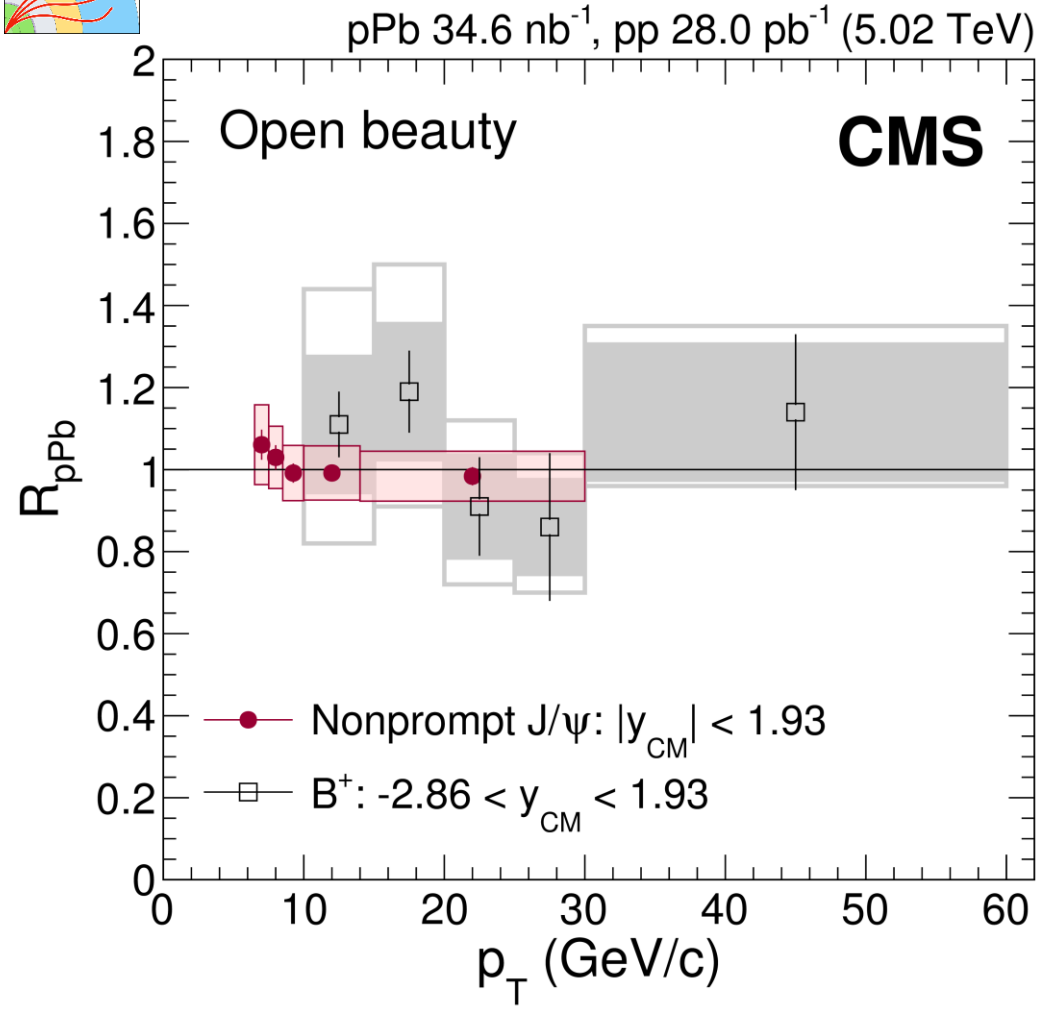
arXiv:1609.03898



- CMS fully reconstructed B mesons and ALICE beauty electron R_{pPb} ~ 1
  - No sizable modification with respect to pp
- Need much higher accuracy data to constraint nPDF or separate models

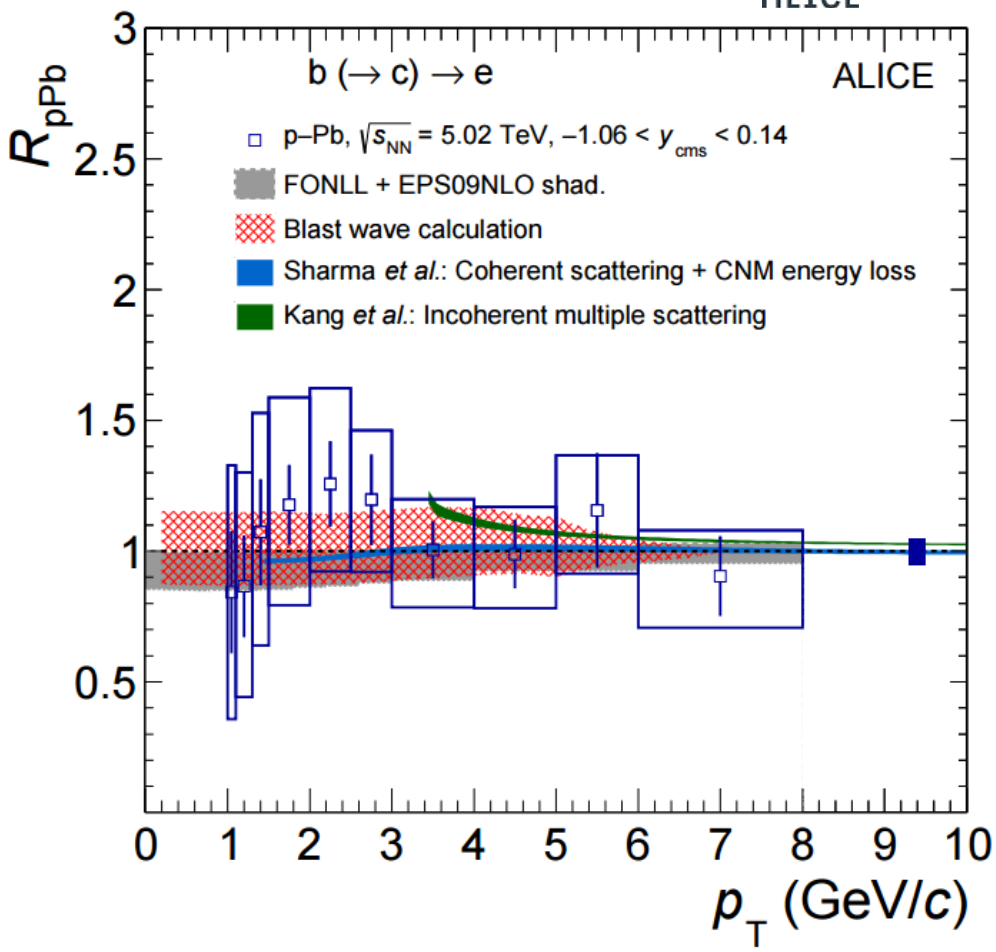
b→J/ψ and b→e R_{pPb} at 5.02 TeV

PRL 116 (2016) 032301
EPJC 77 (2017) 269



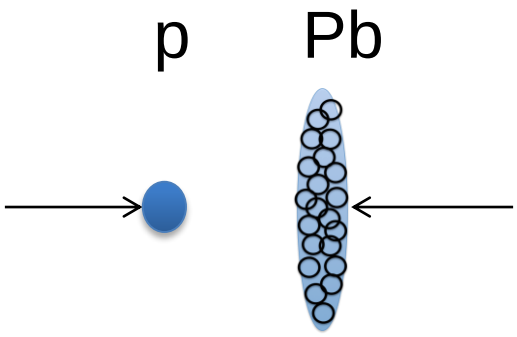
arXiv:1609.03898

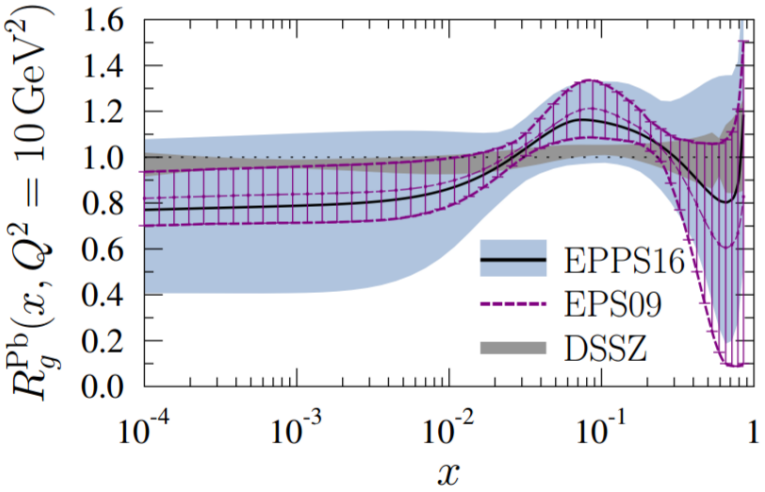
ALICE

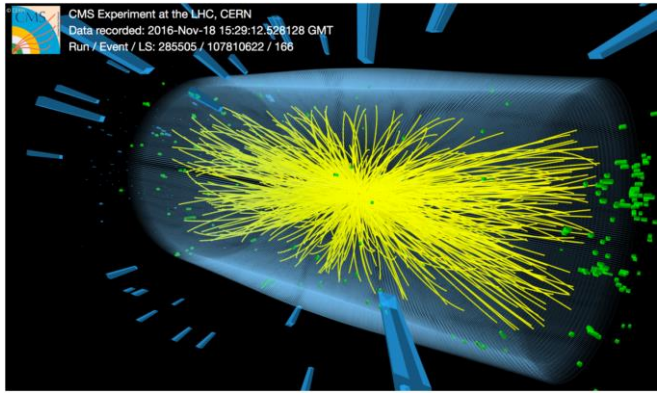


- CMS non-prompt J/ψ shows the modification in pPb < 10%

Open Heavy Flavor in pPb

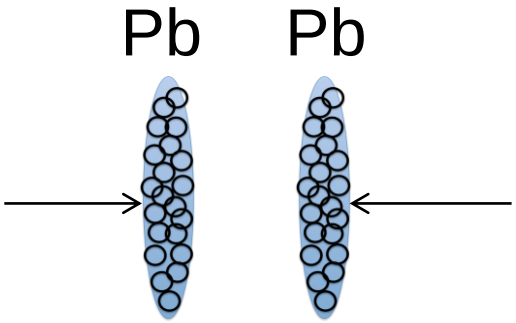


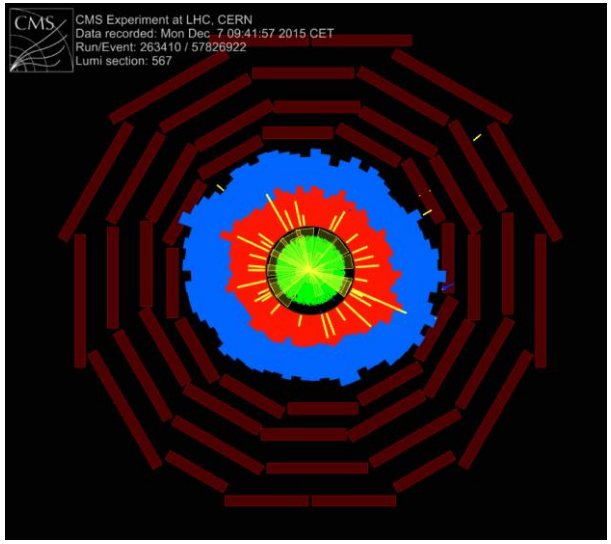


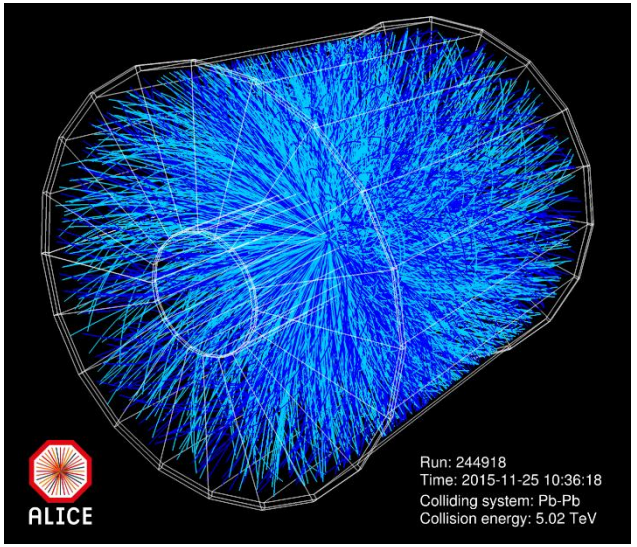


- Test nPDF universality assumption
  - No clear indication of universality violation
- Constrain nPDF and test of the gluon saturation models
  - Data consistent with predictions from saturation models and calculations with nPDF
  - Not accurate enough for constraining the nPDF
- Other cold nuclear effects such as E_{loss}, multiple scattering
  - Need high accuracy data to separate theoretical models

Open Heavy Flavor in PbPb



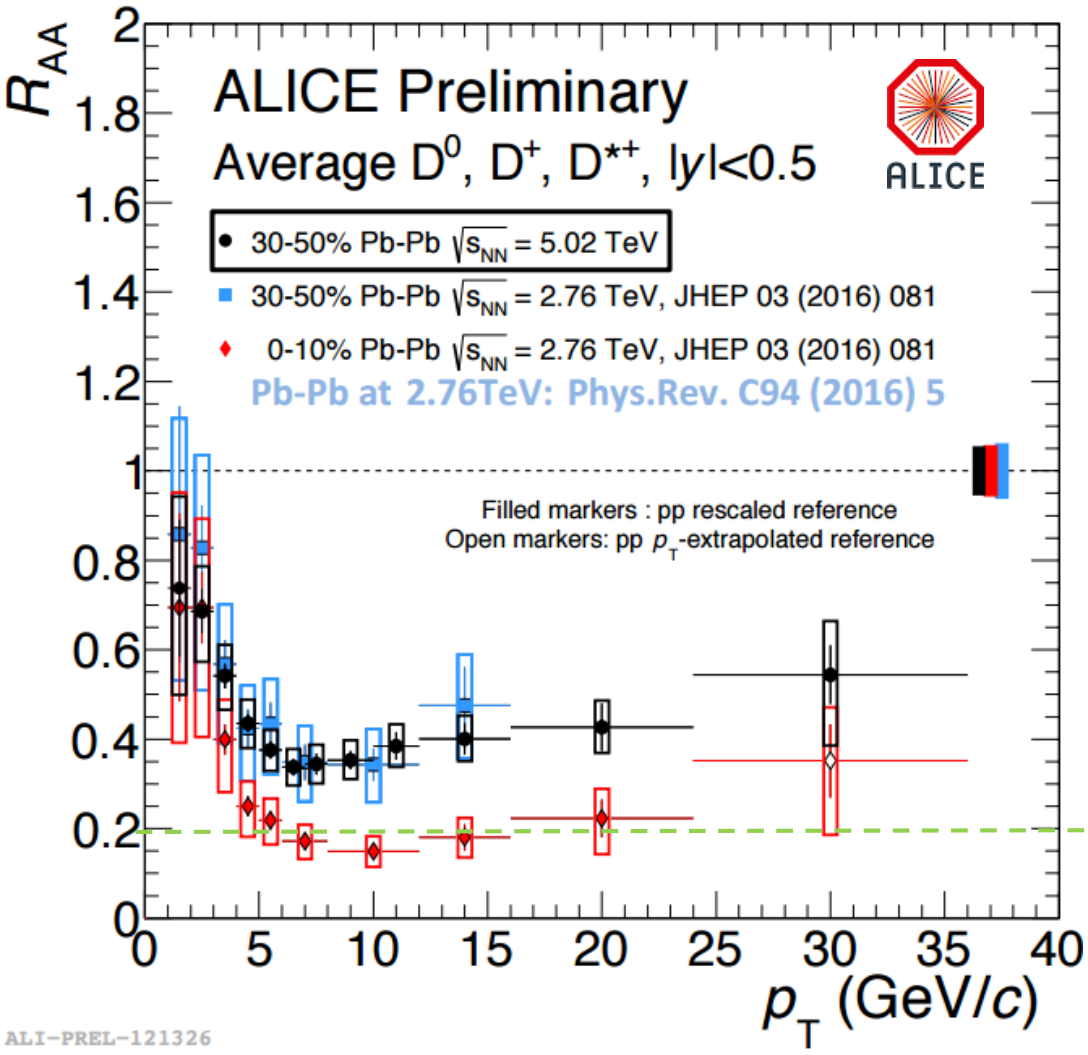




- Difference between PbPb at 2.76 TeV and 5.02 TeV?
- Flavor dependence of parton energy loss?
- The role of shadowing effect?
- The role of collisional energy loss?
- “Thermalization” of charm and beauty

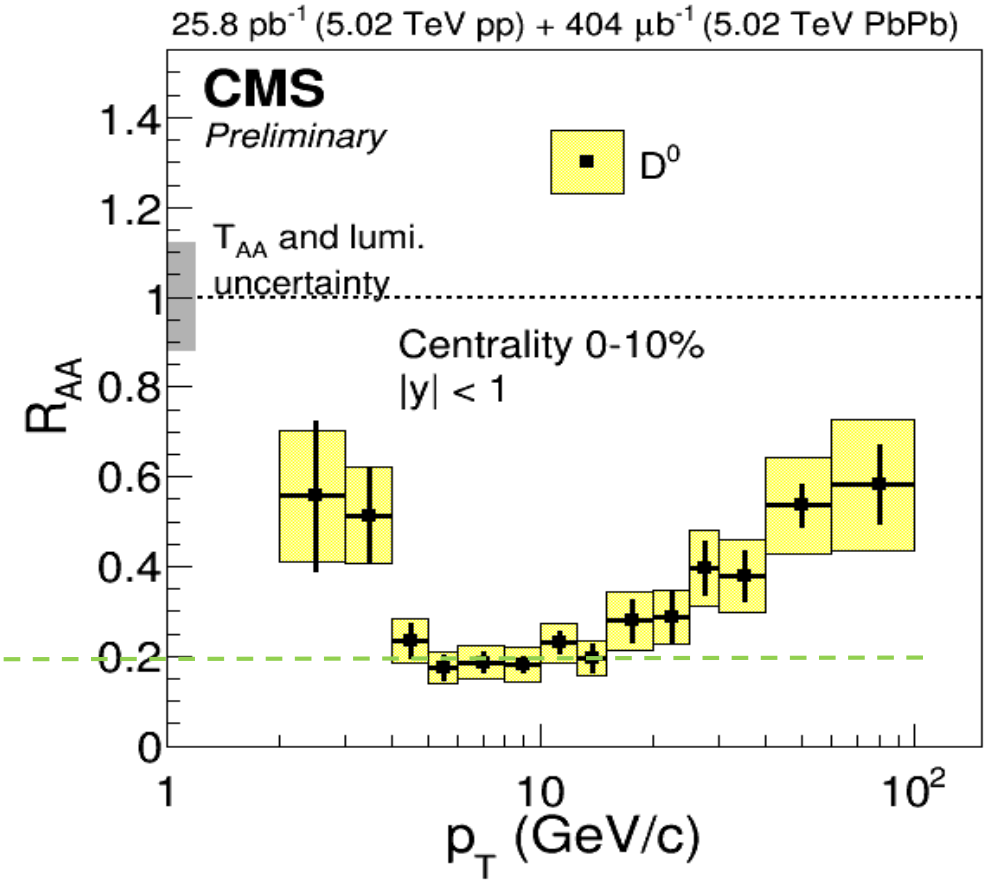
D meson R_{AA} in PbPb

ALICE D R_{AA} **|y|<0.5** at **2.76 TeV**



CMS D^0 R_{AA} **|y|<1** at **5.02 TeV**

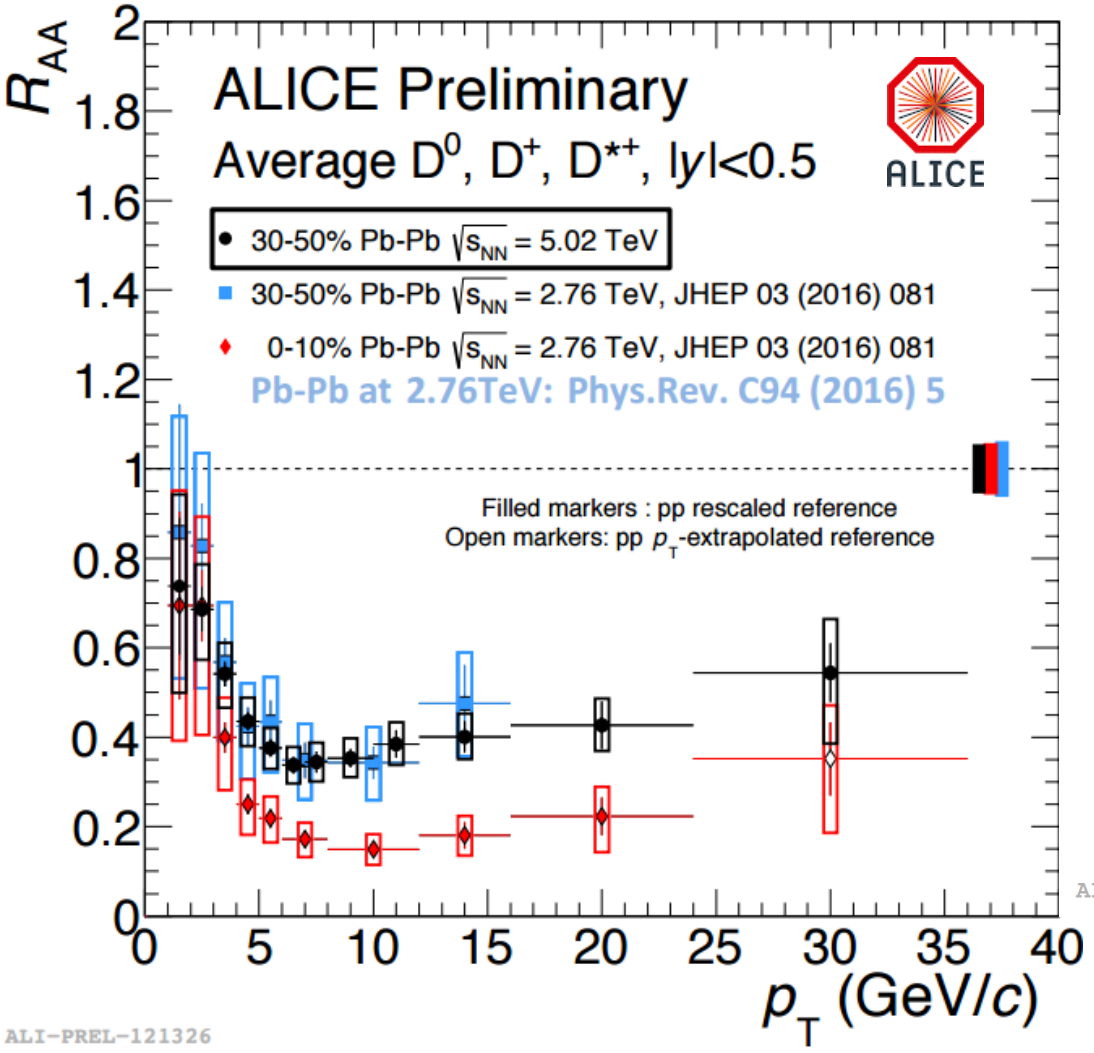
CMS-PAS-HIN-16-001



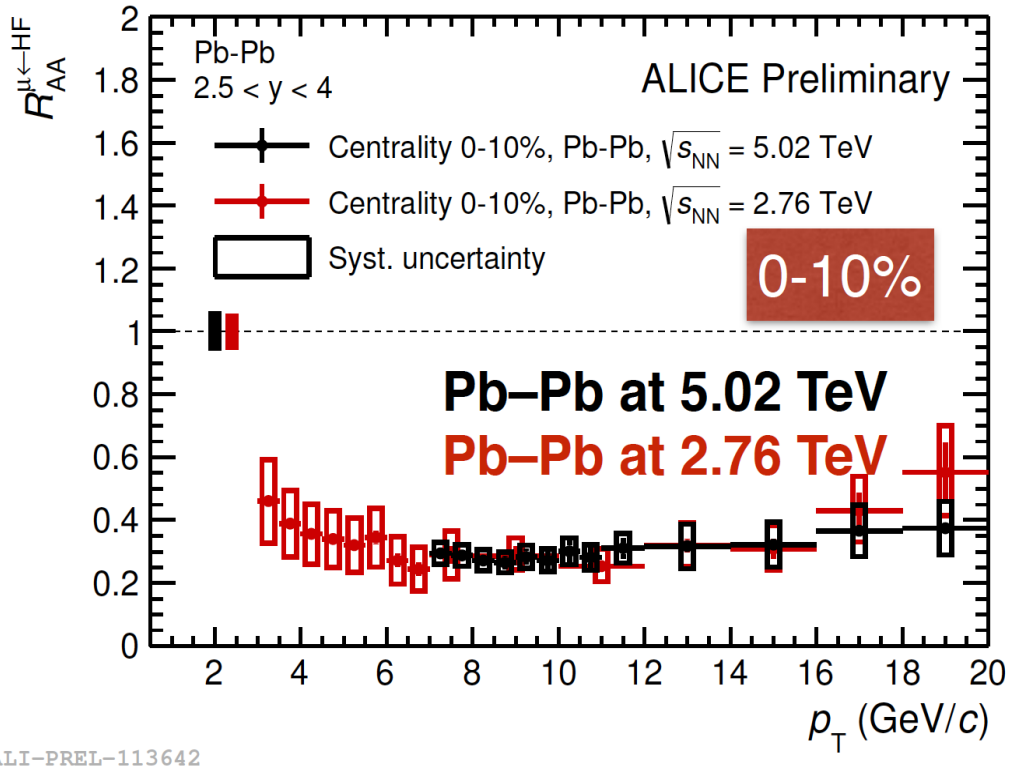
- Similar suppression in PbPb at 2.76 and 5.02 TeV
- CMS D^0 R_{AA}: established a rising trend vs. D^0 p_T

D and HF muon R_{AA} in PbPb

ALICE D R_{AA} **|y|<0.5** at **2.76 TeV**

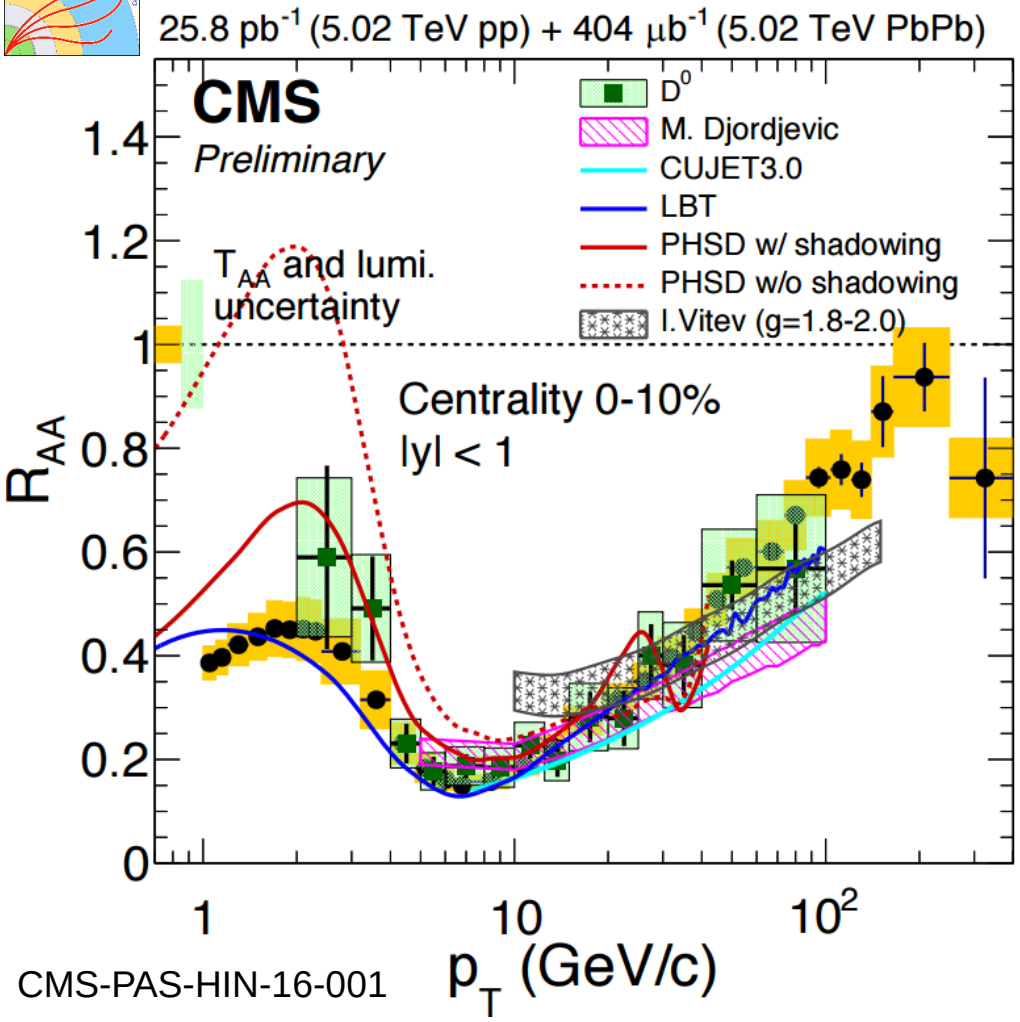


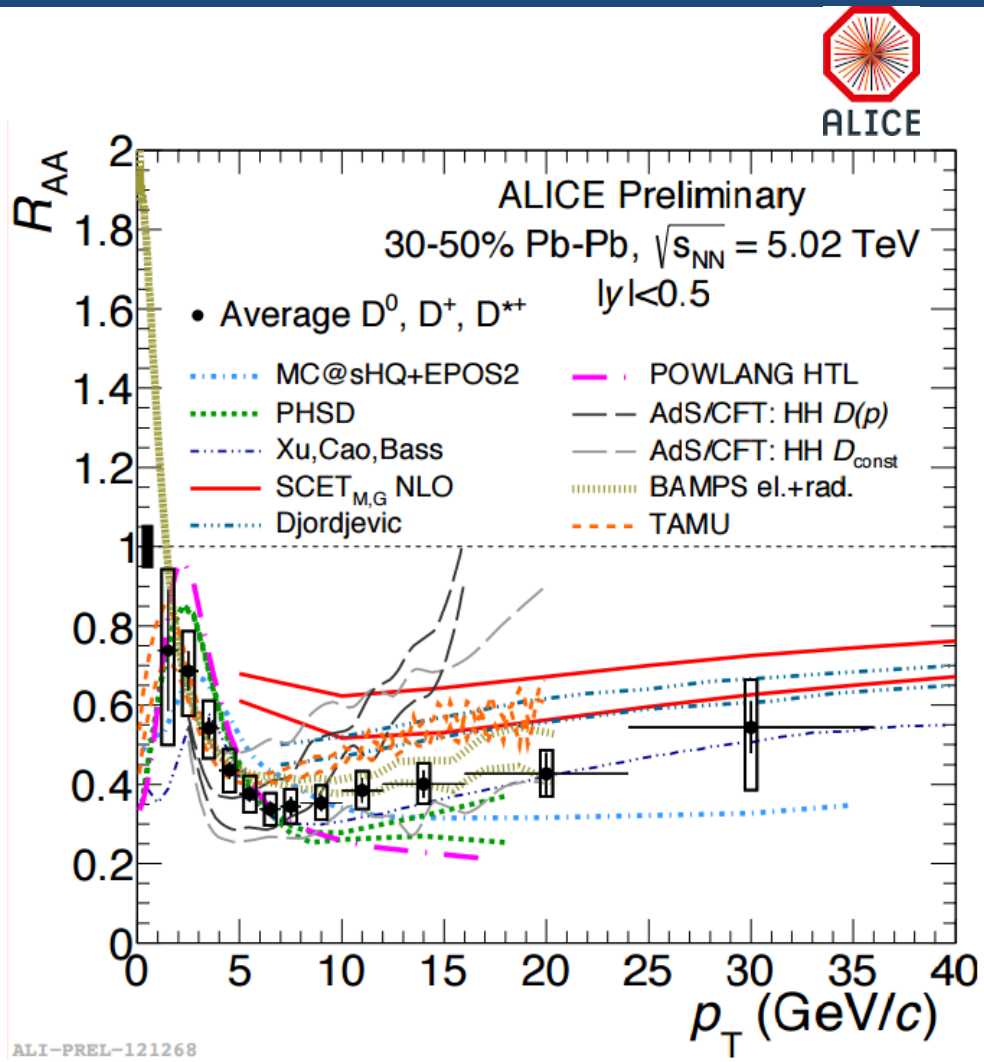
ALICE HF muon R_{AA} **2.5<y<4** at **5.02** and **2.76 TeV**



- Similar suppression in PbPb at 2.76 and 5.02 TeV

D R_{AA} vs. Theoretical Models





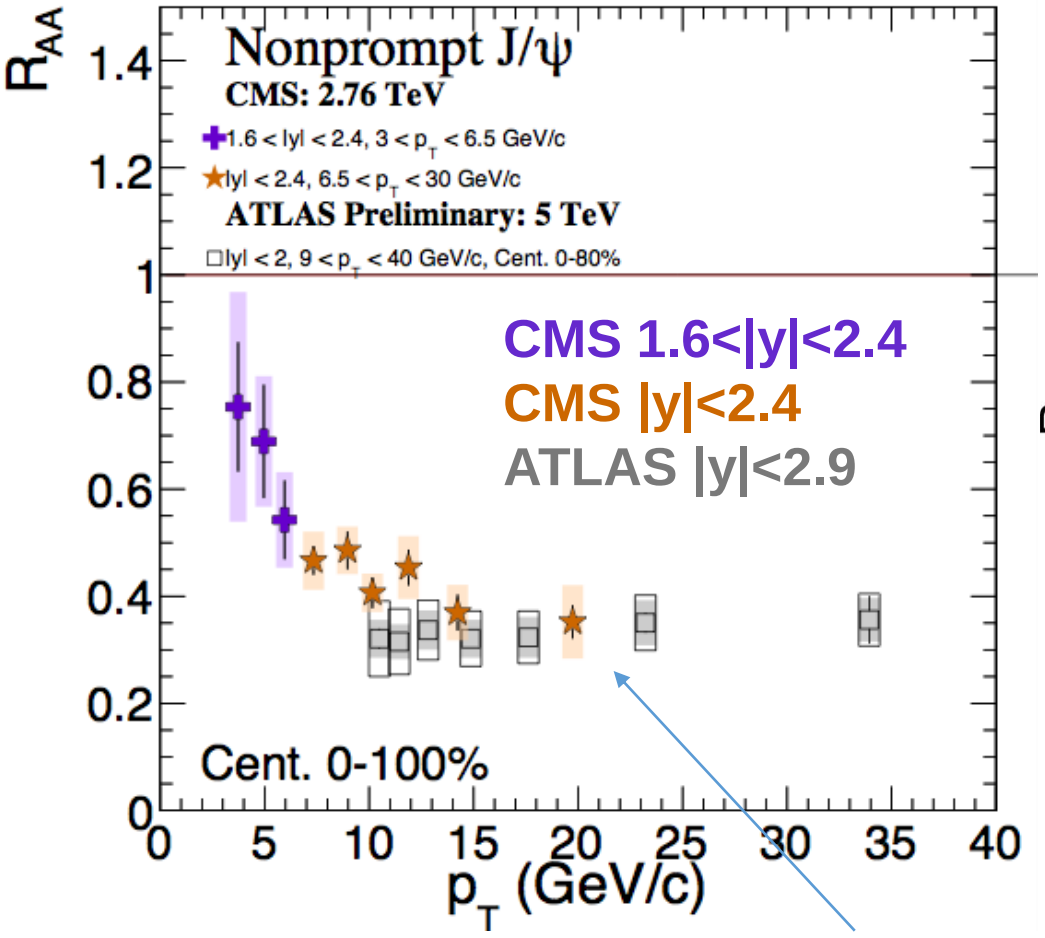
D^0 R_{AA} seems to favor calculations that include:

- Both collisional and radiative energy loss
- Shadowing effect in nPDF

- Models almost fill the full R_{AA} vs p_T phase space..
- Time to rule out some "theatrical models"

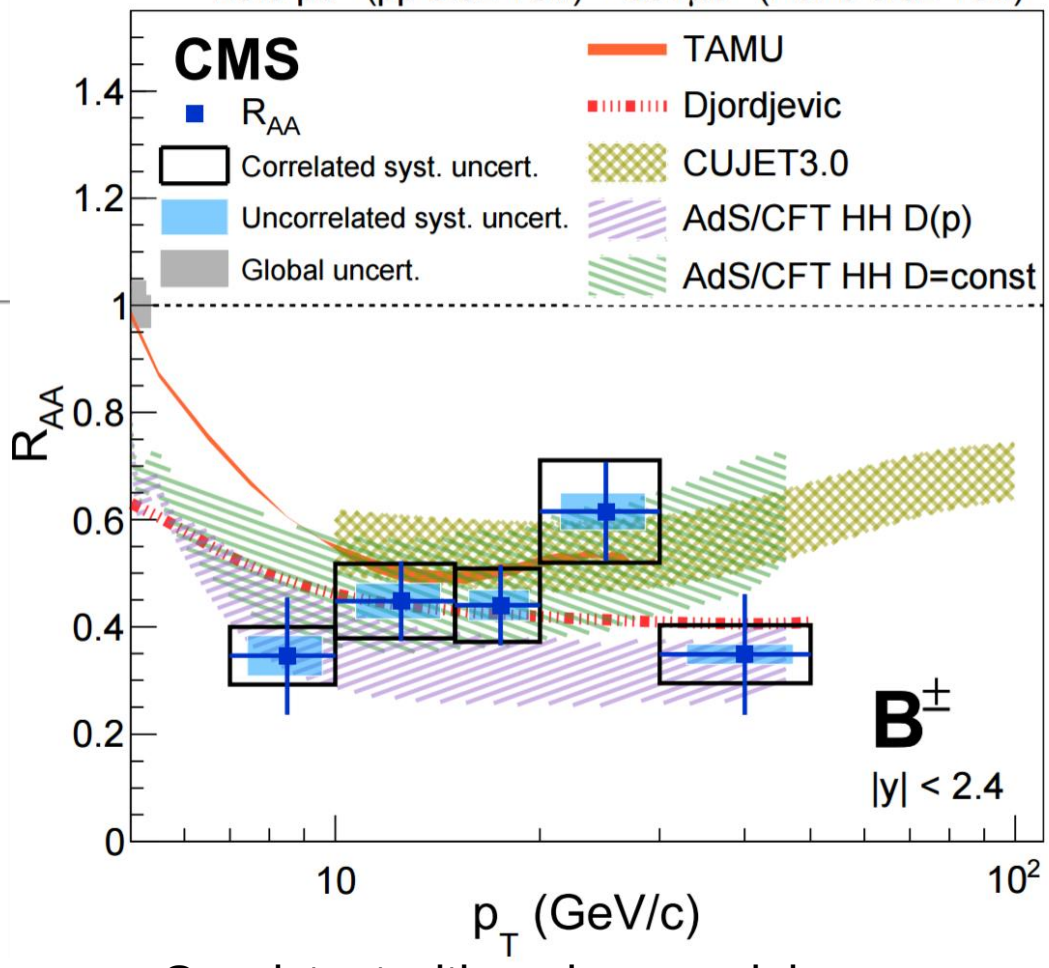
Beauty Suppression

Significant suppression of B mesons and non-prompt J/ψ



Similar suppression between **CMS 2.76 TeV** and **ATLAS 5 TeV** results

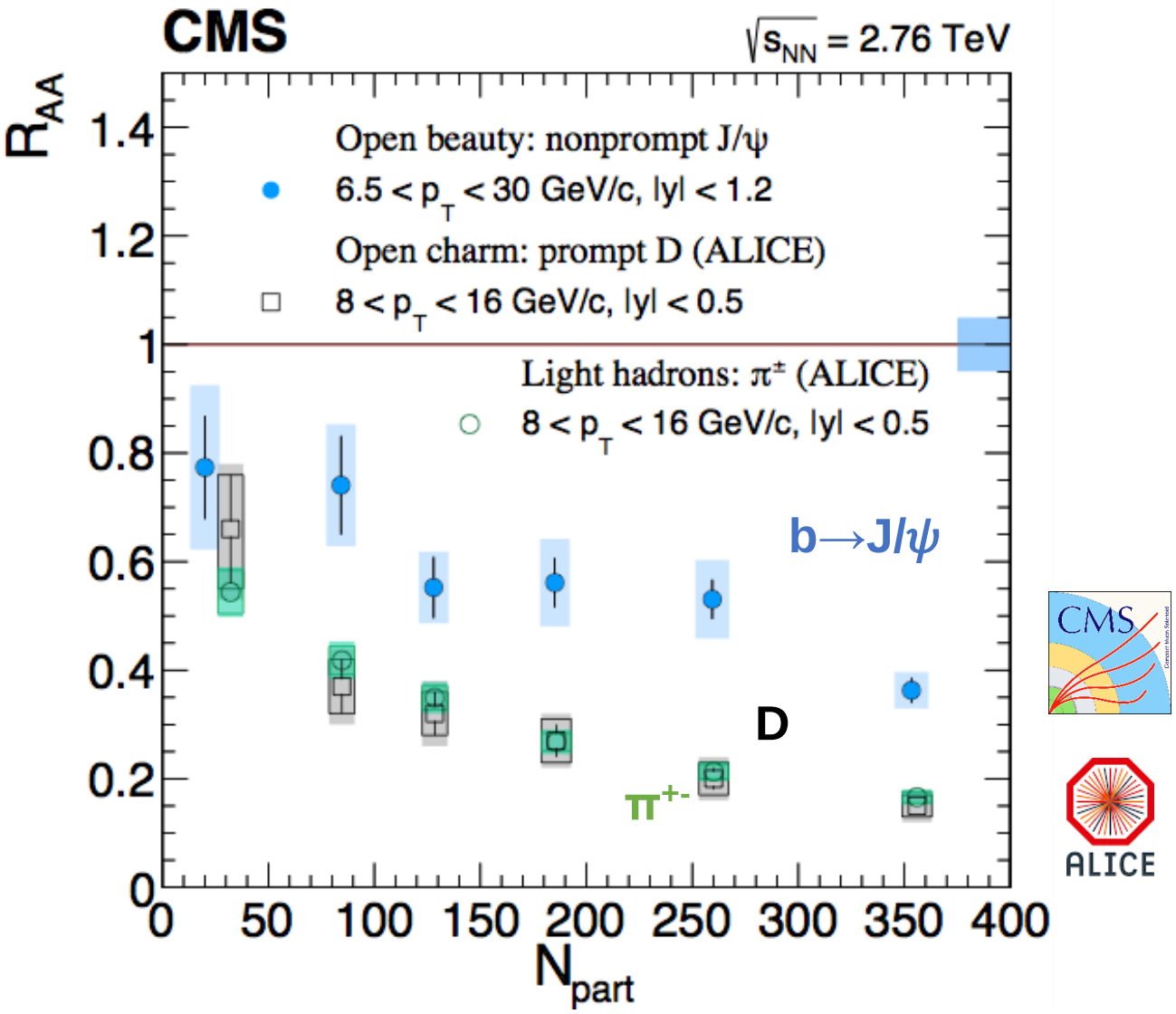
arXiv: 1705.04727
Submitted to PRL



- Consistent with various models
- Not accurate enough to extract detailed underlying mechanism from models

Flavor Dependence of E_{loss} at 2.76 TeV

EPJC 77 (2017) 252



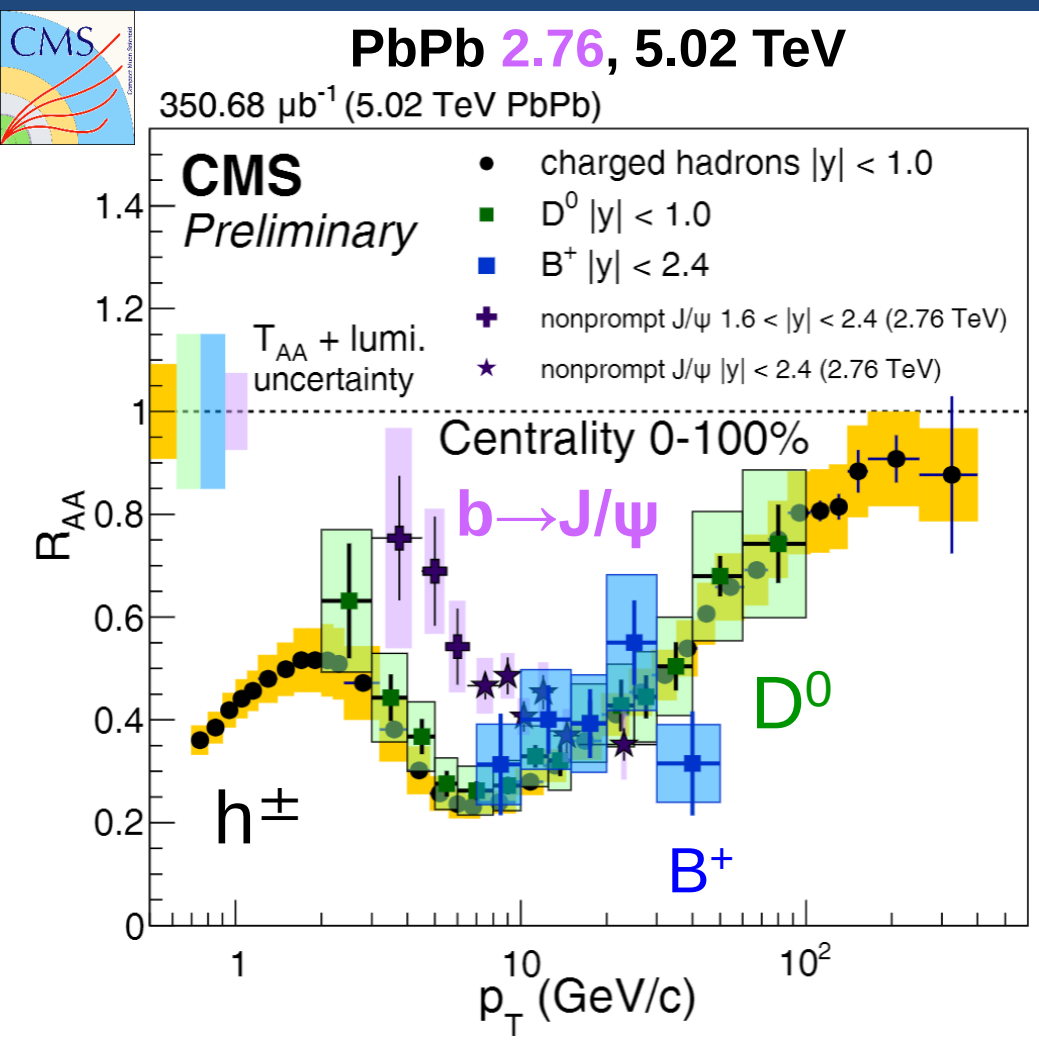
CMS Non-prompt J/ψ

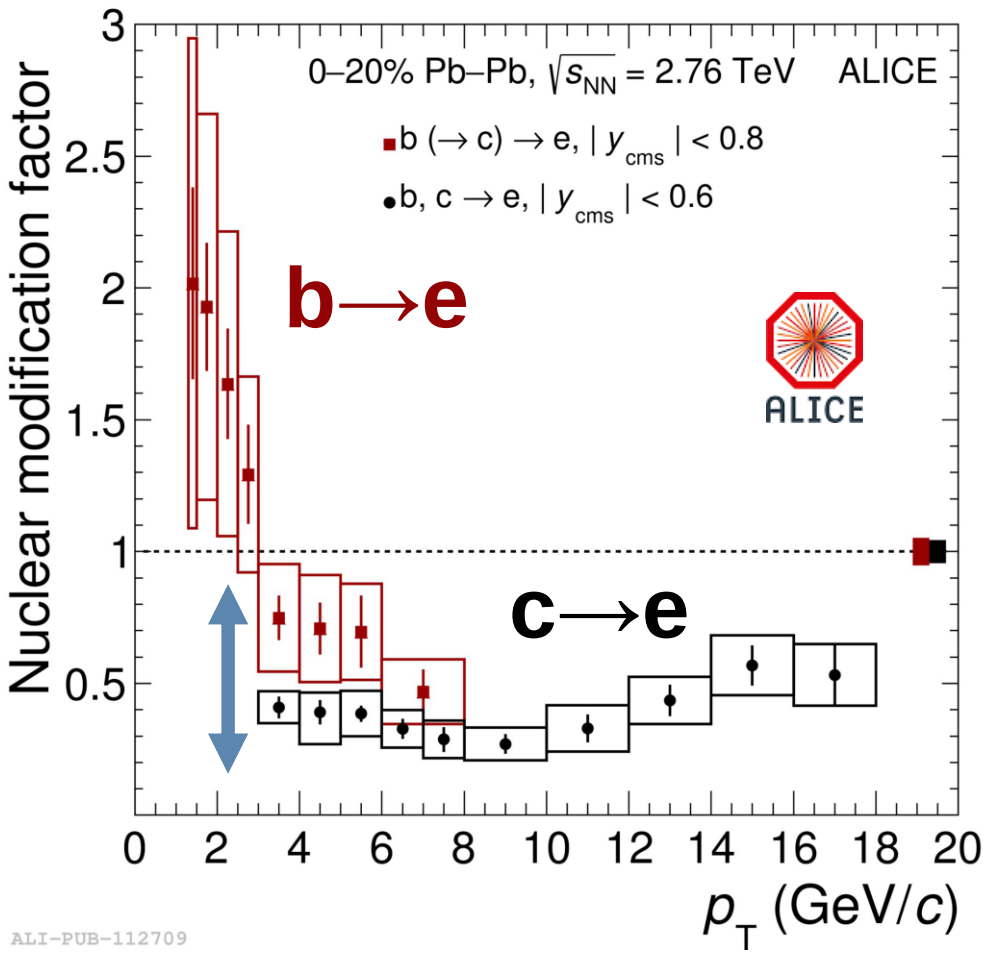
ALICE D mesons

ALICE π+-

- Final result of non-prompt J/ψ R_{AA} from CMS

Flavor Dependence of Parton Energy Loss



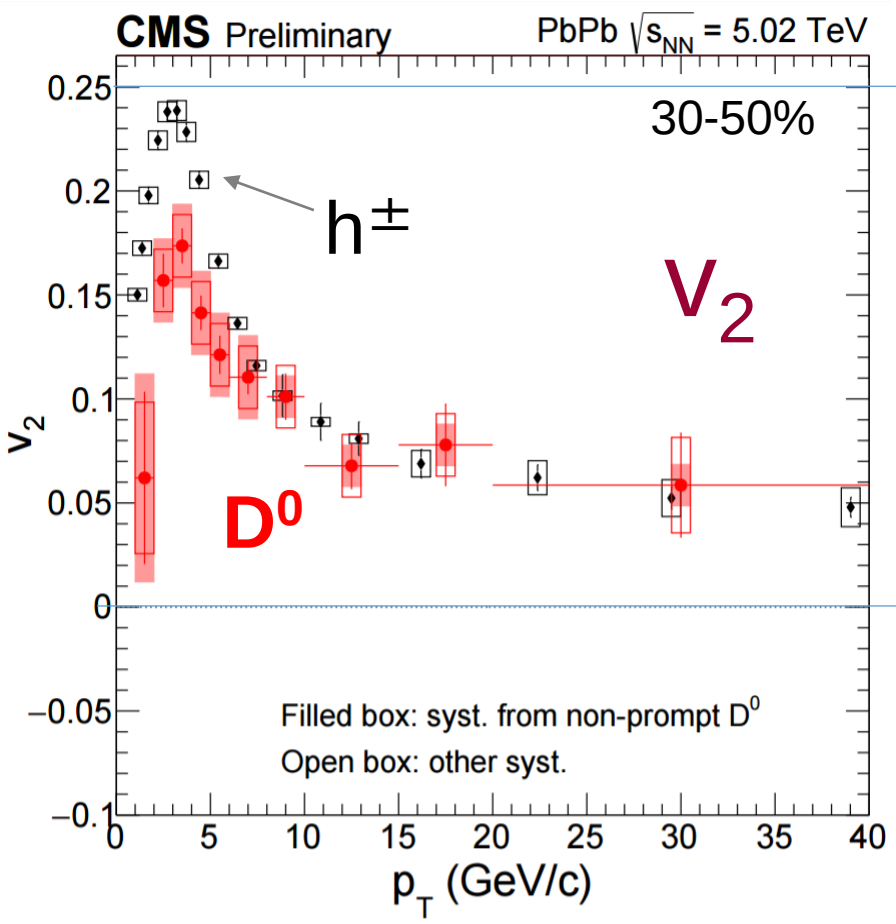


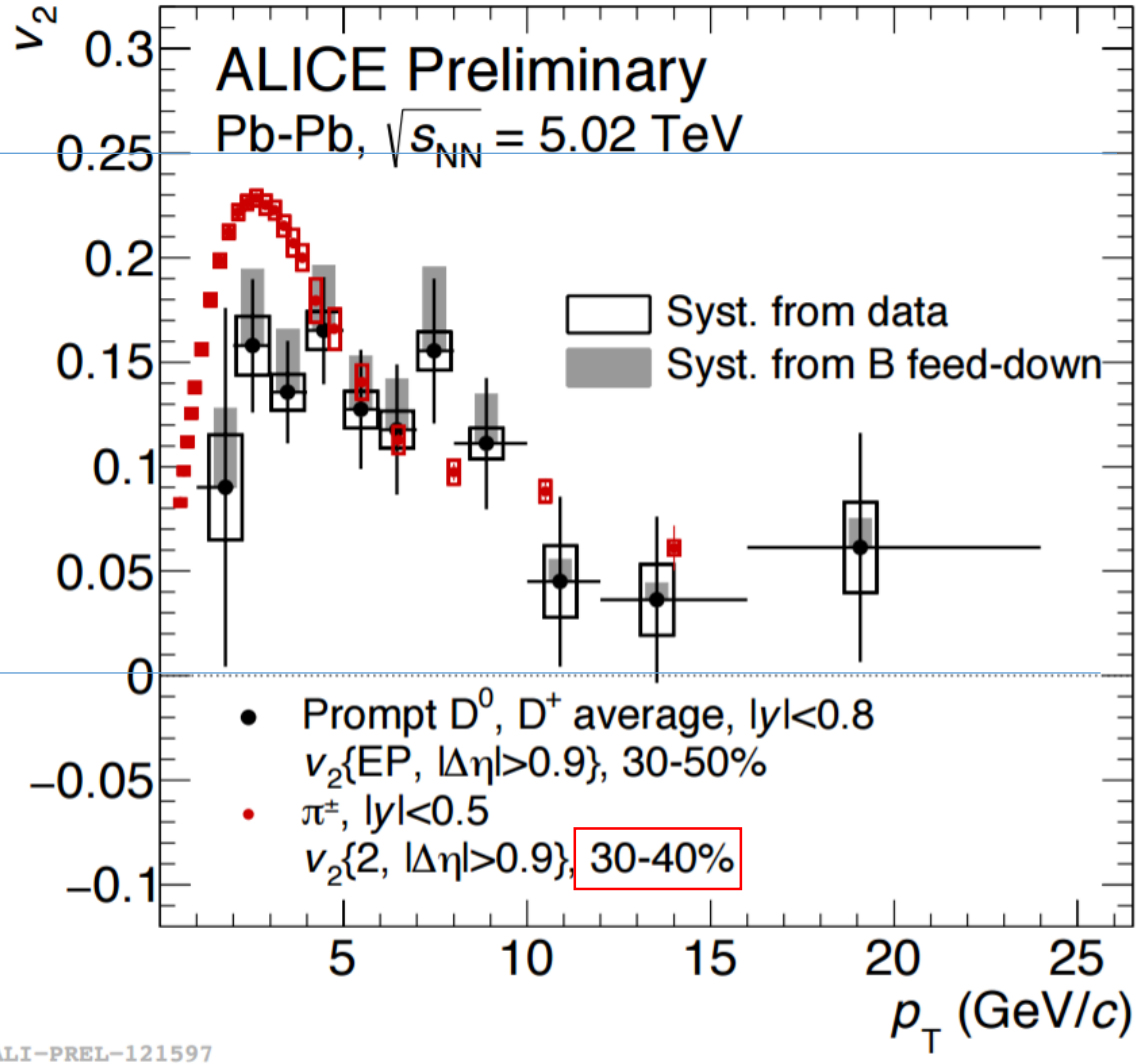
- No significant flavor dependence of R_{AA} at high p_T
- p_T < 10 GeV: Difference between between **b→J/ψ** and other particles

- Hint of less suppression from b→e data than c→e

D^0 CMS-PAS-HIN-16-001	Charged hadrons arXiv: 1611.01664 JHEP 04 (2017) 039	J/ψ arXiv: 1610.00613 EPJC 77 (2017) 252
B^+ arXiv 1705.04727		

The Life of Charm Quark in the Soup



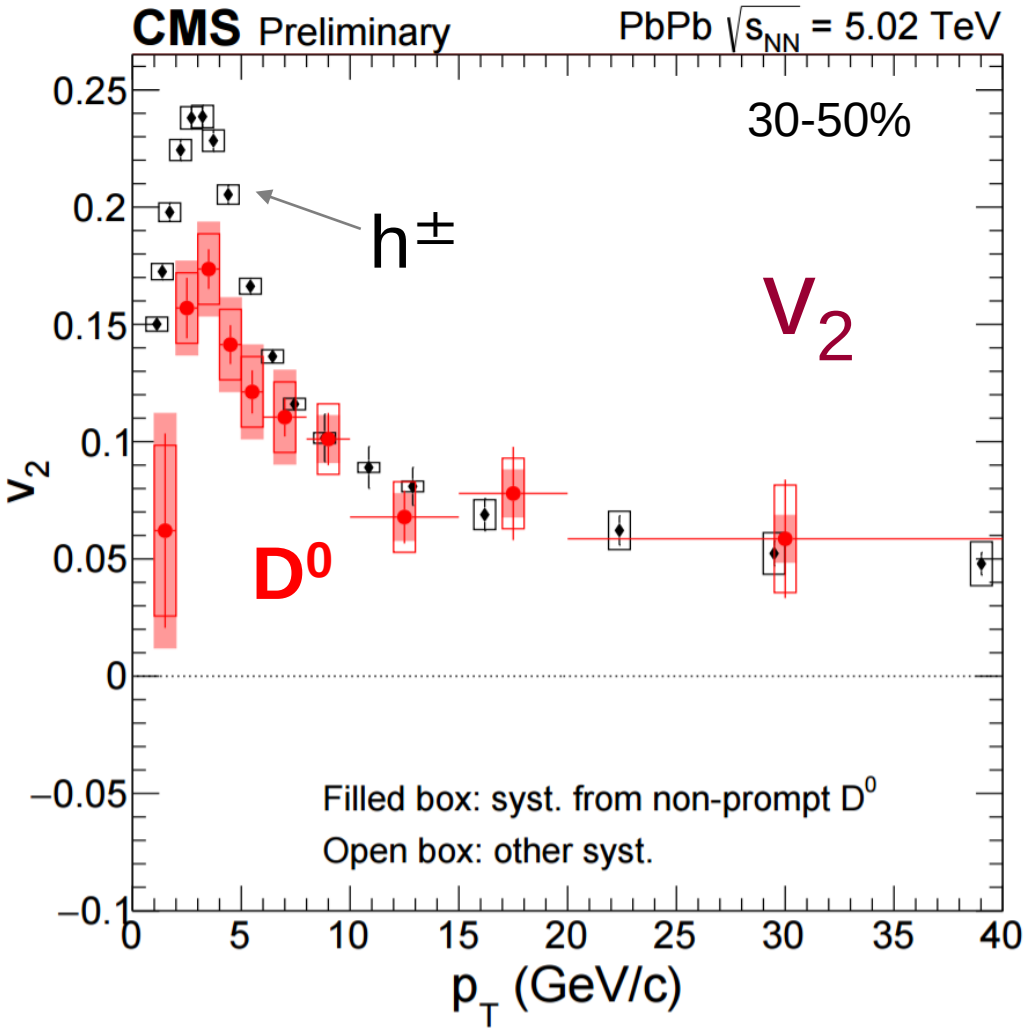


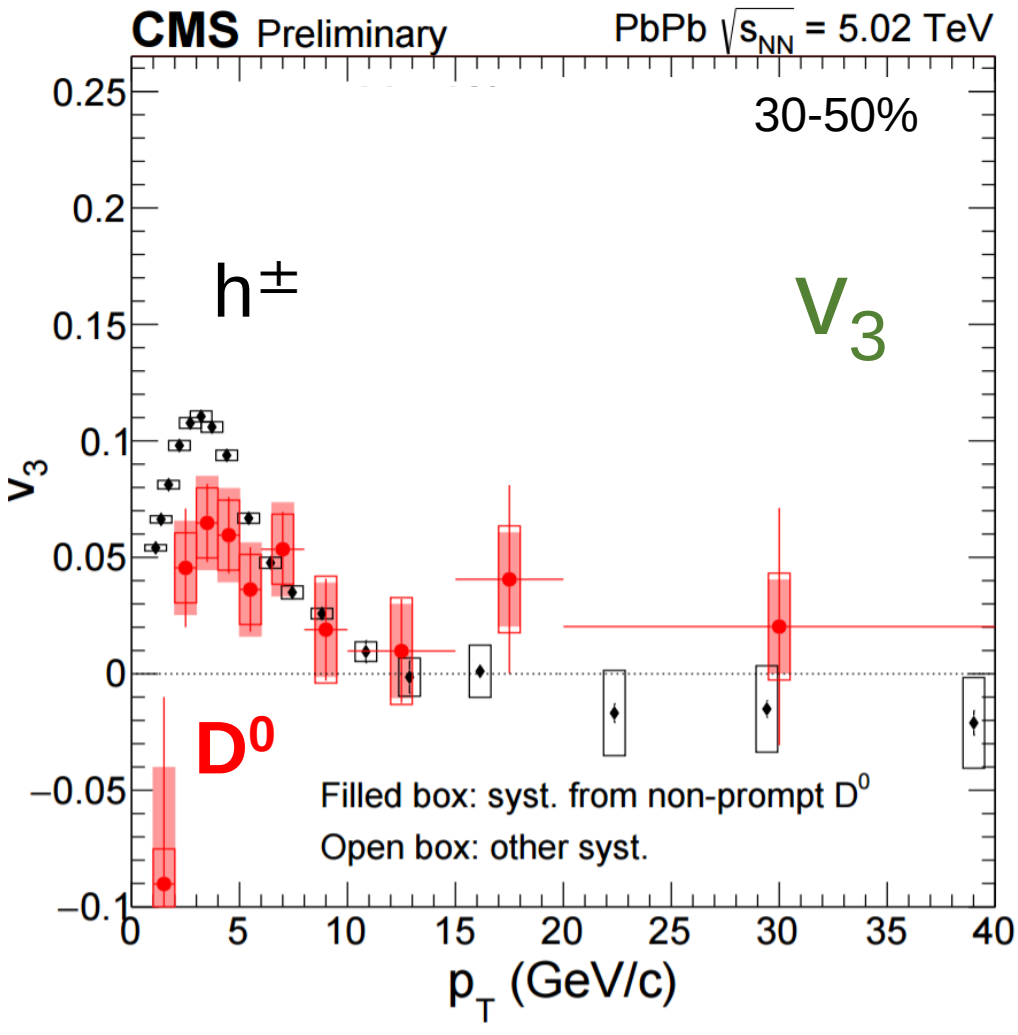
- At low p_T: **D^0 v_2** signal is significantly lower than that of charged particles
- At high p_T: **D^0 v_2 ≈ charged particle v_2**

  Same parton energy loss picture from high p_T D^0 R_{AA} and v_2 measurements

CMS-PAS-HIN-16-007

The Life of Charm Quark in the Soup

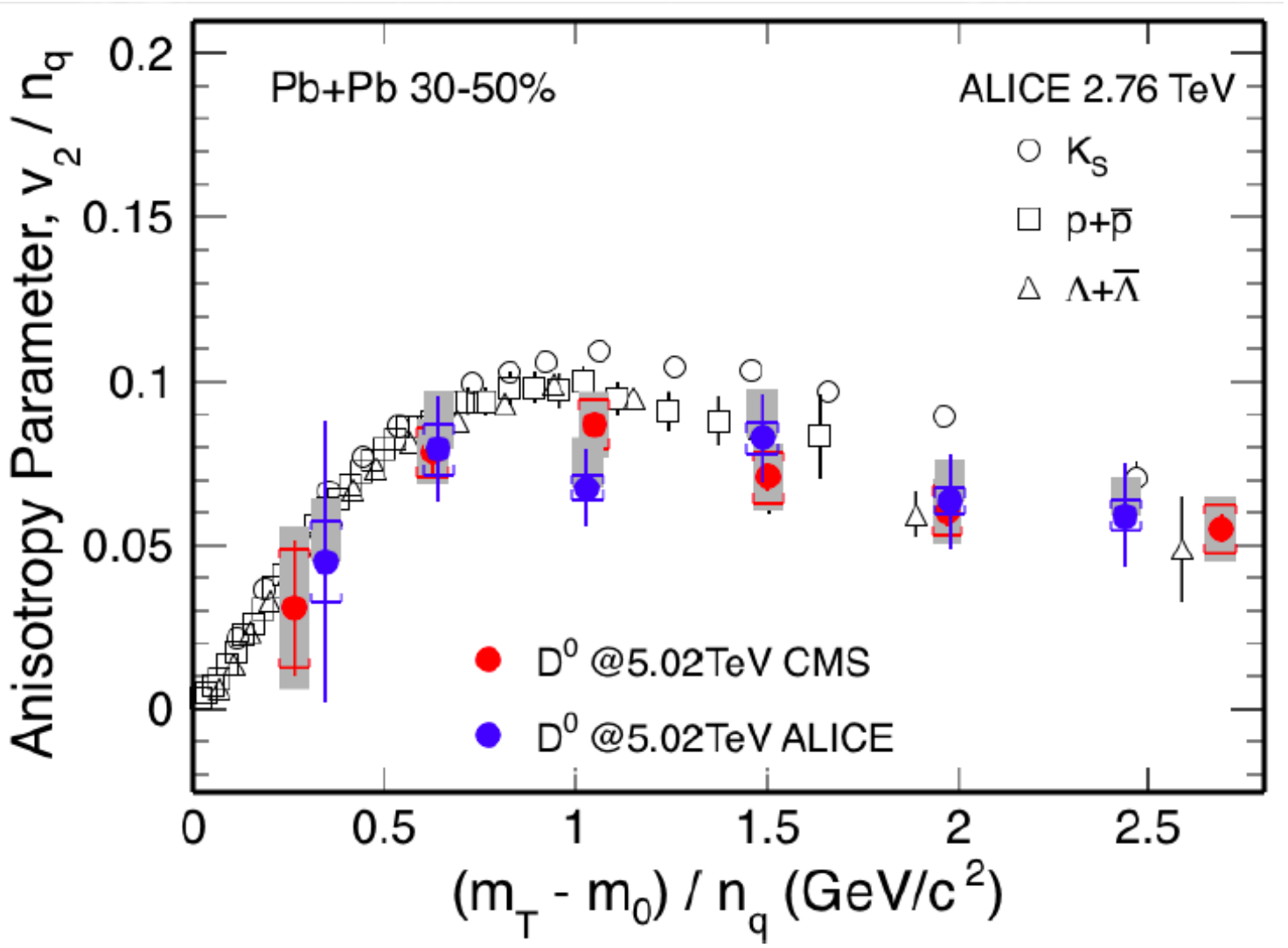




- At low p_T: **D^0 v_3** signal is significantly lower than that of charged particles
- At high p_T: **D^0 v_3 ≈ charged particle v_3** , consistent with 0

CMS-PAS-HIN-16-007

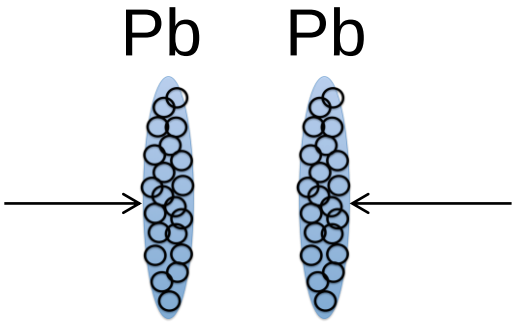
D^0 v_2 compared to light hadrons

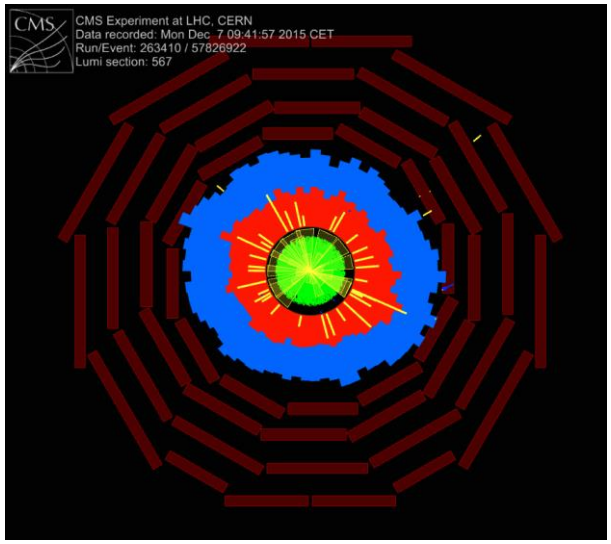


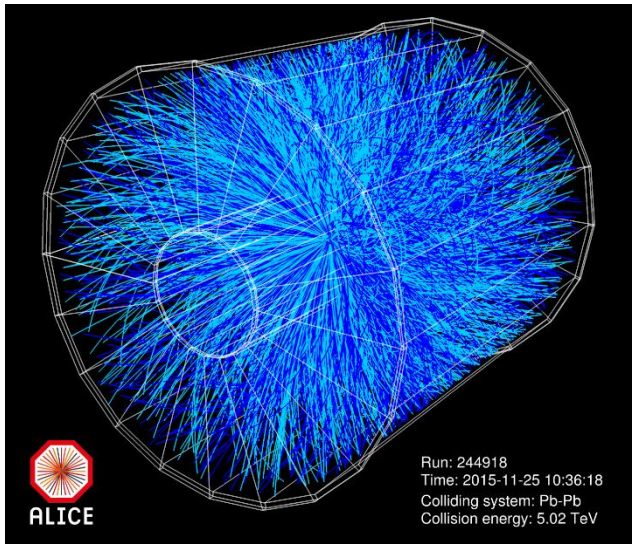
D^0 v_2 seems to fall on the trend of light flavor

Xin Dong (QM2017)

Open Heavy Flavor in PbPb



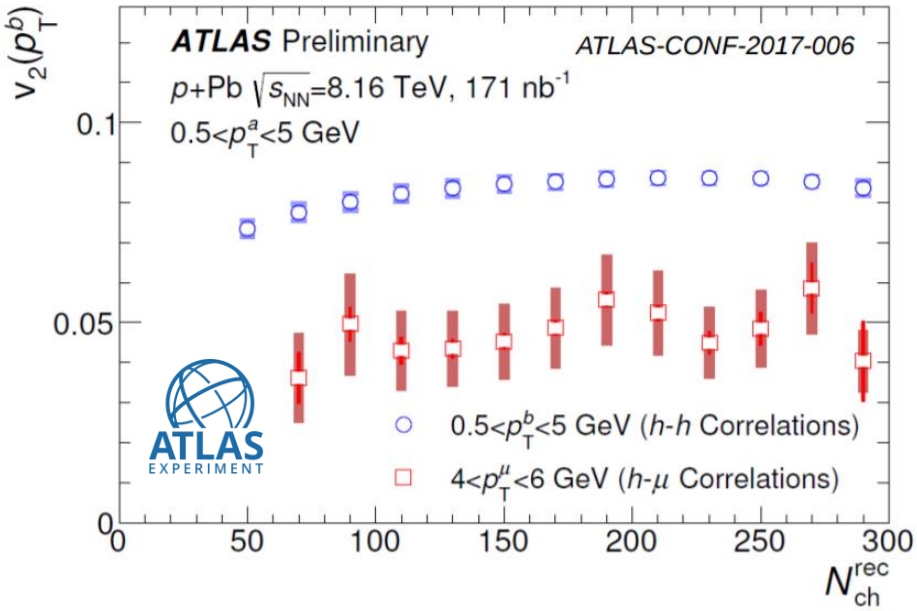


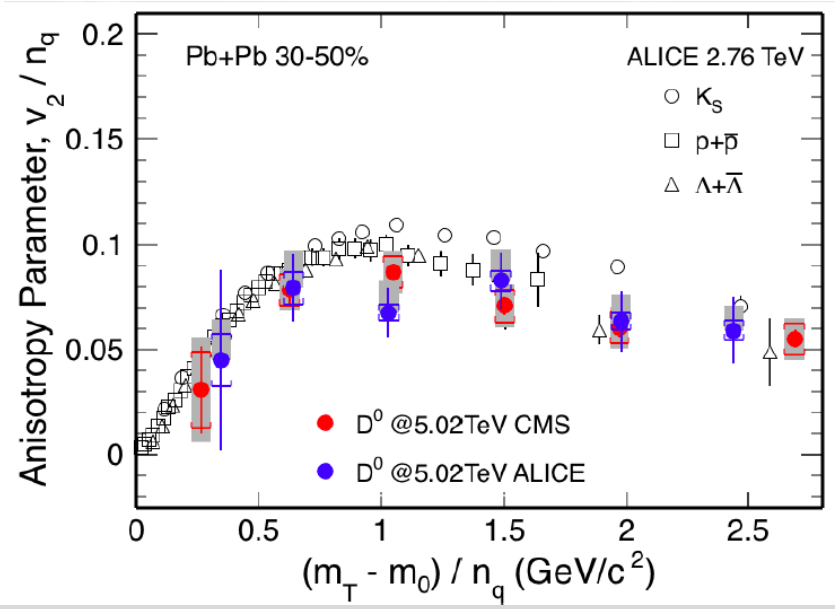


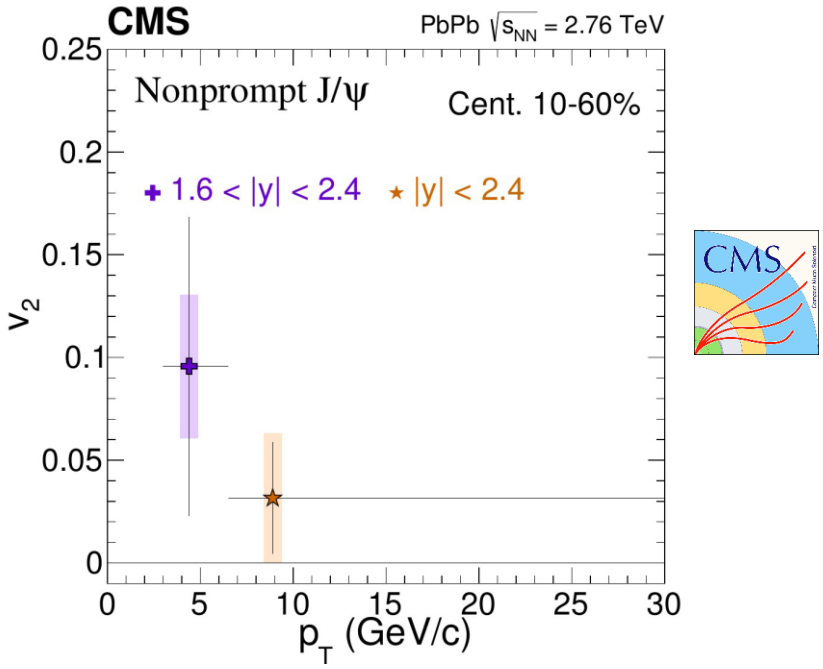
- Difference between PbPb at 2.76 TeV and 5.02 TeV?
  - No significant difference in R_{AA} (in both HF and light flavor)
- Flavor dependence of parton energy loss?
  - Clear meson flavor dependence of R_{AA} at low p_T
- The role of shadowing effect?
  - Model with shadowing seems to give a better description of D^0 data
- The role of collisional energy loss?
  - Need higher accuracy data / other observables
- "Thermalization" of charm and beauty
  - Significant D^0 v_2 and v_3 signal, indication of (partial) thermalizaton of charm
  - Need more data to conclude for beauty

(Unanswered) Questions

- How does the strongly interacting medium emerge from an asymptotic free theory (QCD)?
  - Origin of charm meson v_2 (and v_3)?
    - How do they get "thermalized"?
    - How does the azimuthal anisotropy of light flavor "transfer" to charm mesons?
  - Does beauty quark flow?
  - What is the origin of the HF muon v_2 signal in pPb collisions?

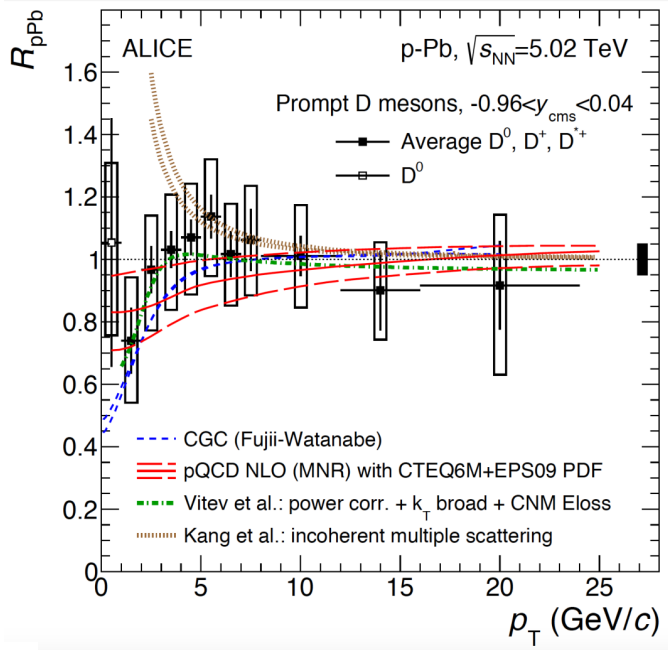


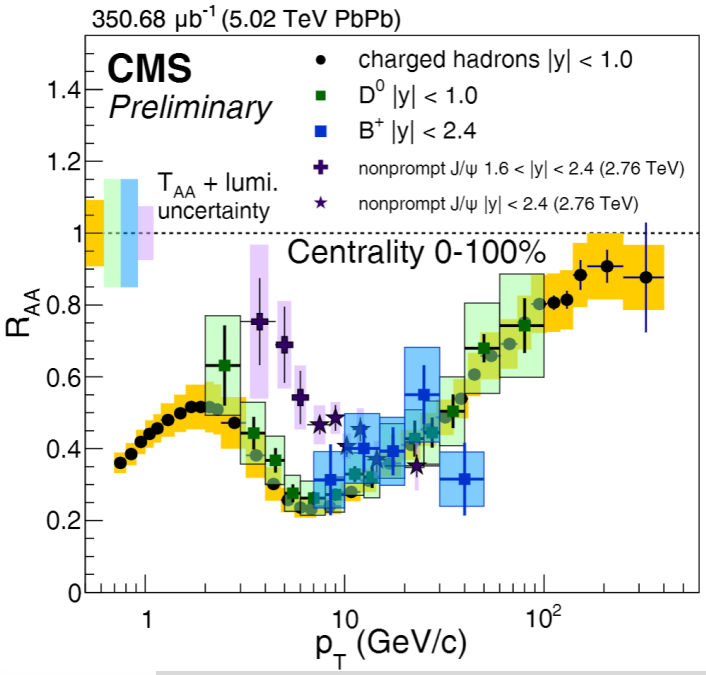


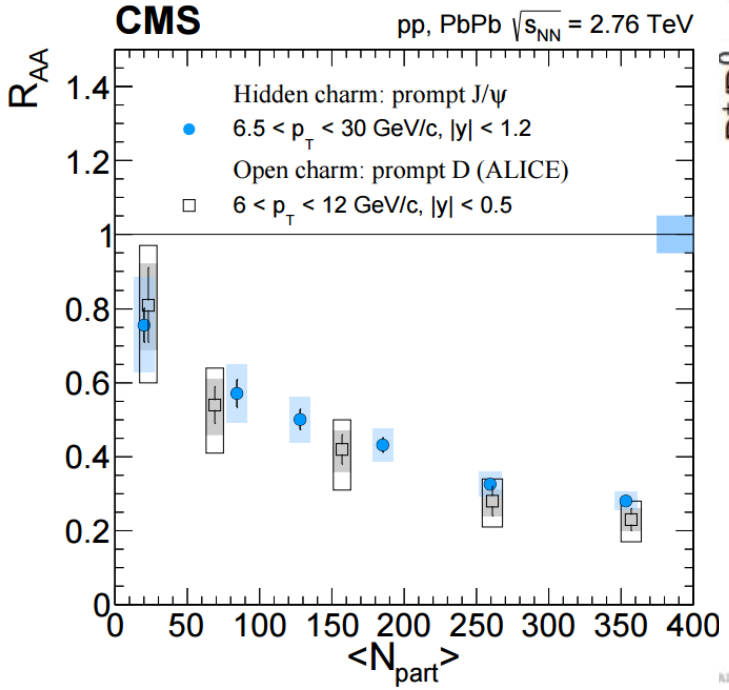


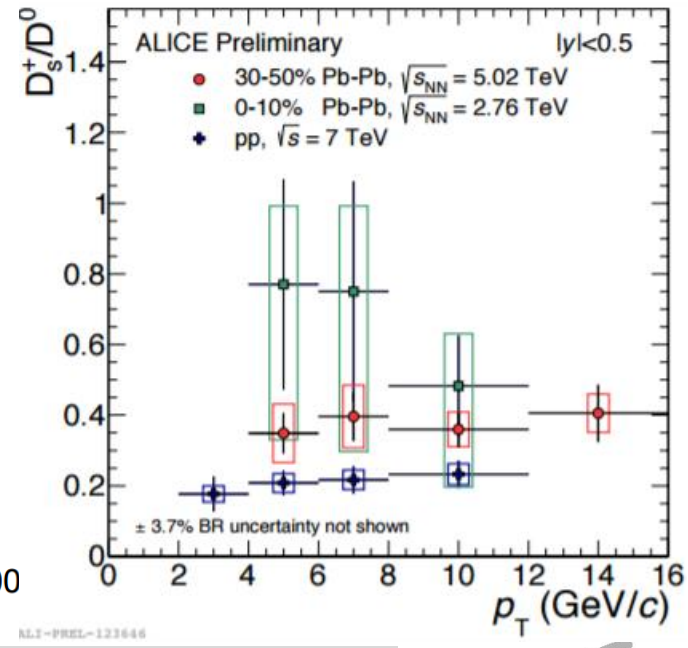
(Unanswered) Questions

- Extraction of the medium property:
  - What is the role of shadowing effect?
  - What is the origin of the meson flavor dependence of R_{AA}?
    - The role of recombination
    - Need stronger evidence of collision energy loss and pin down the relative contribution of collisional and radiative energy loss
- Why is the hidden and open charm suppression so similar?

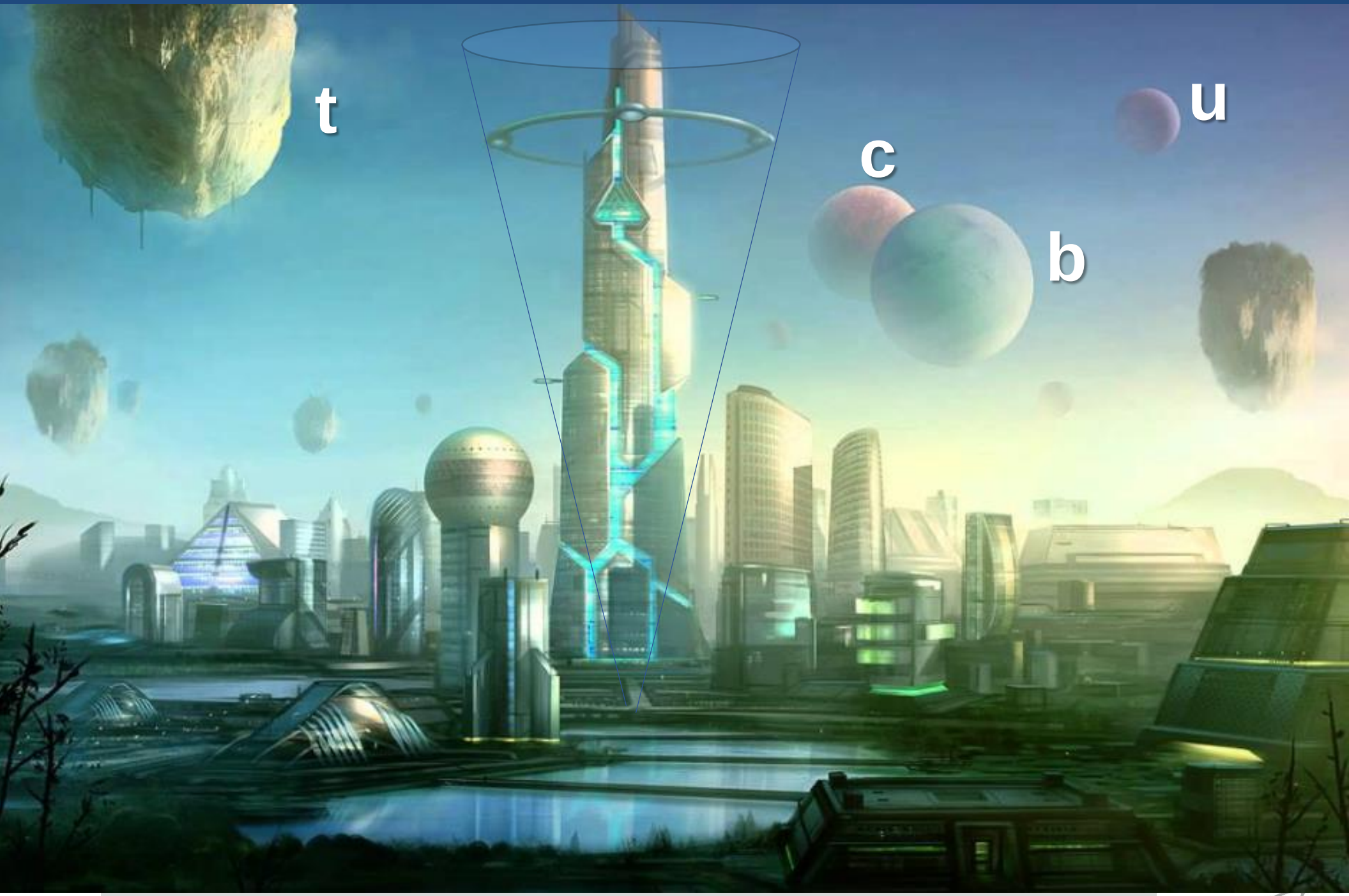




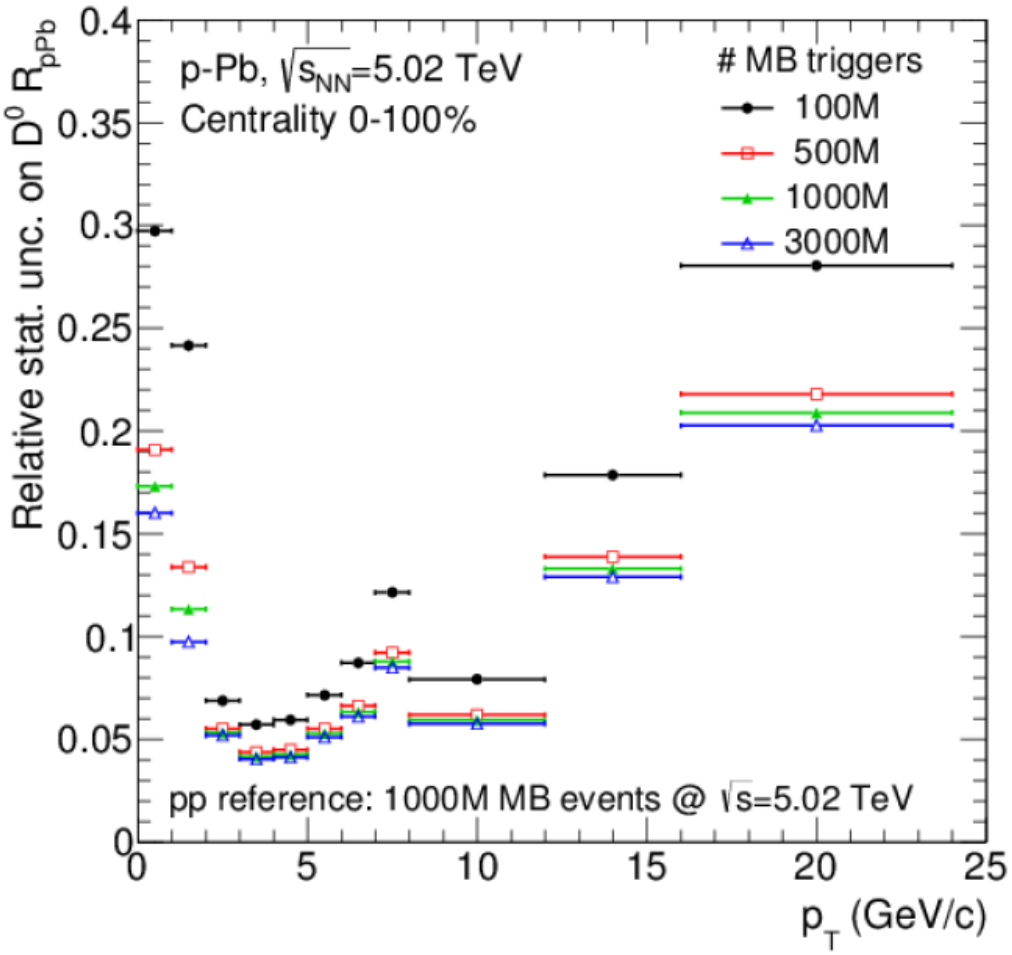


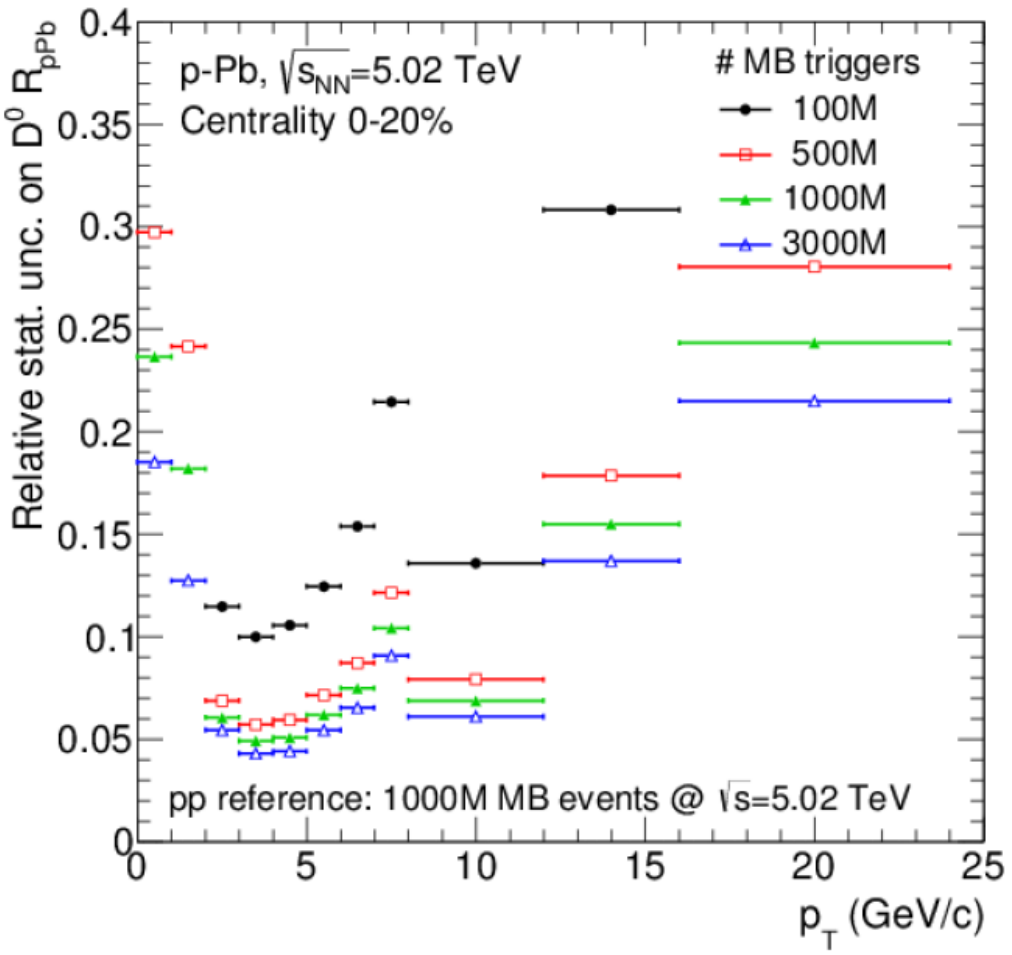


Outlook



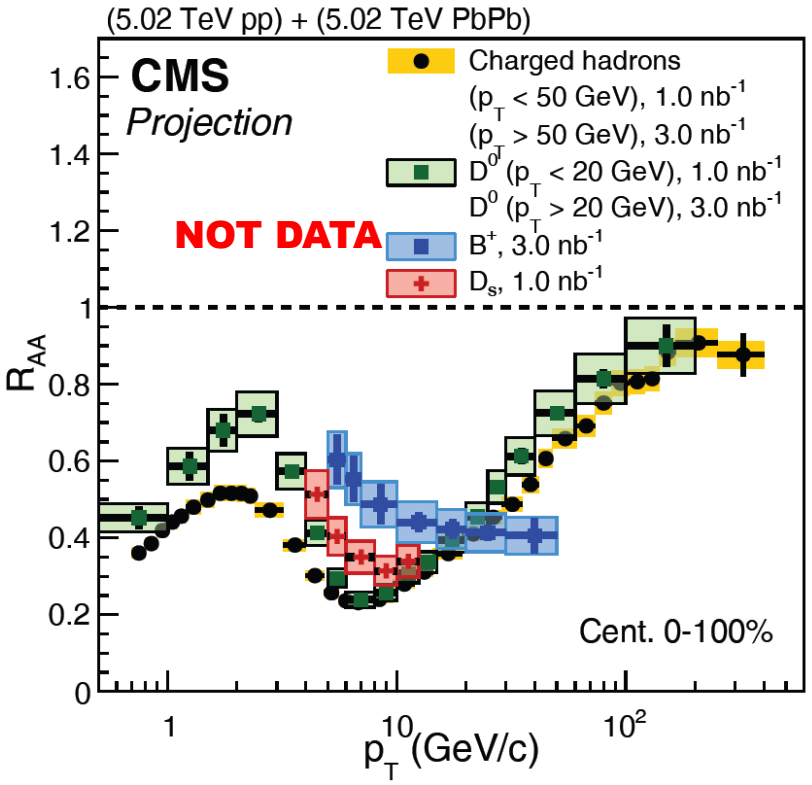
Projected Performance on D R_{pPb}

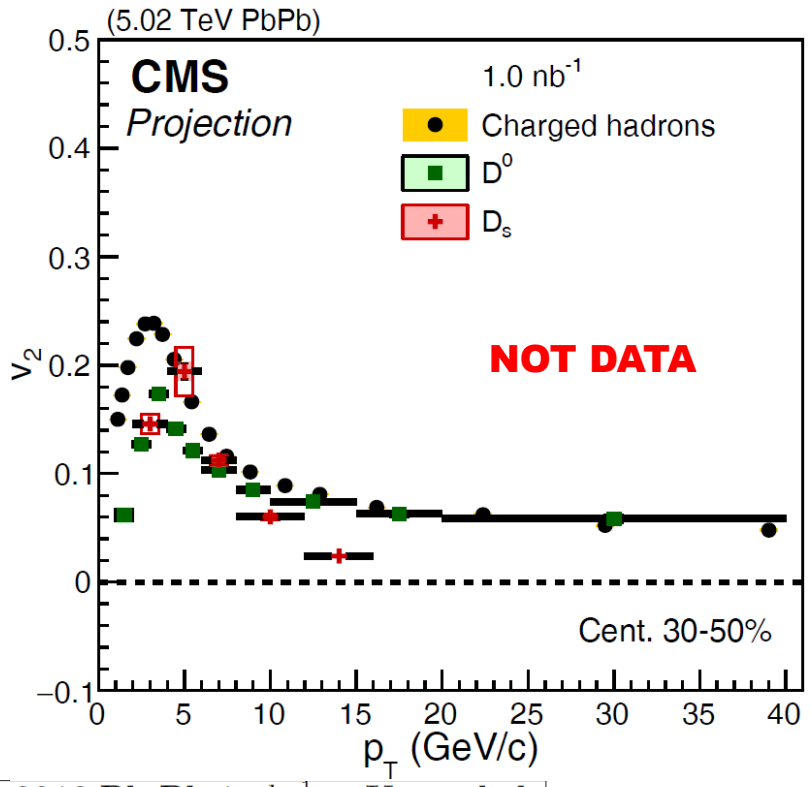




High precision measurement with 2016 pPb data

Projected Performance in 2018 – Run III





	Current 0.04 nb^{-1} + Present System		2018 Pb-Pb 1 nb^{-1} + Upgraded System	
Observables	p_T min	Statistical Uncertainty	p_T min	Statistical Uncertainty
$D^0 R_{AA}$	2	15%	0.5 - 1	10%
$D_s R_{AA}$	~ 4	20%	< 4	4%
$\Lambda_c R_{AA}$	10	$> 20\%$	< 10	4%
$B \to D R_{AA}$	6	20%	2	10%
$B^+(D^0\pi) R_{AA}$	Not accessible		~ 4	
Low p_T c and b jets	Not accessible		~ 30	
$D^0 v_2$ $(= 0.06)$	1	80%	0.5 - 1	18%
$D_s v_2$	Not accessible		~ 4	
$B \to D v_2$	Not accessible		~ 2	
$\Lambda_c v_2$	Not accessible		~ 6	

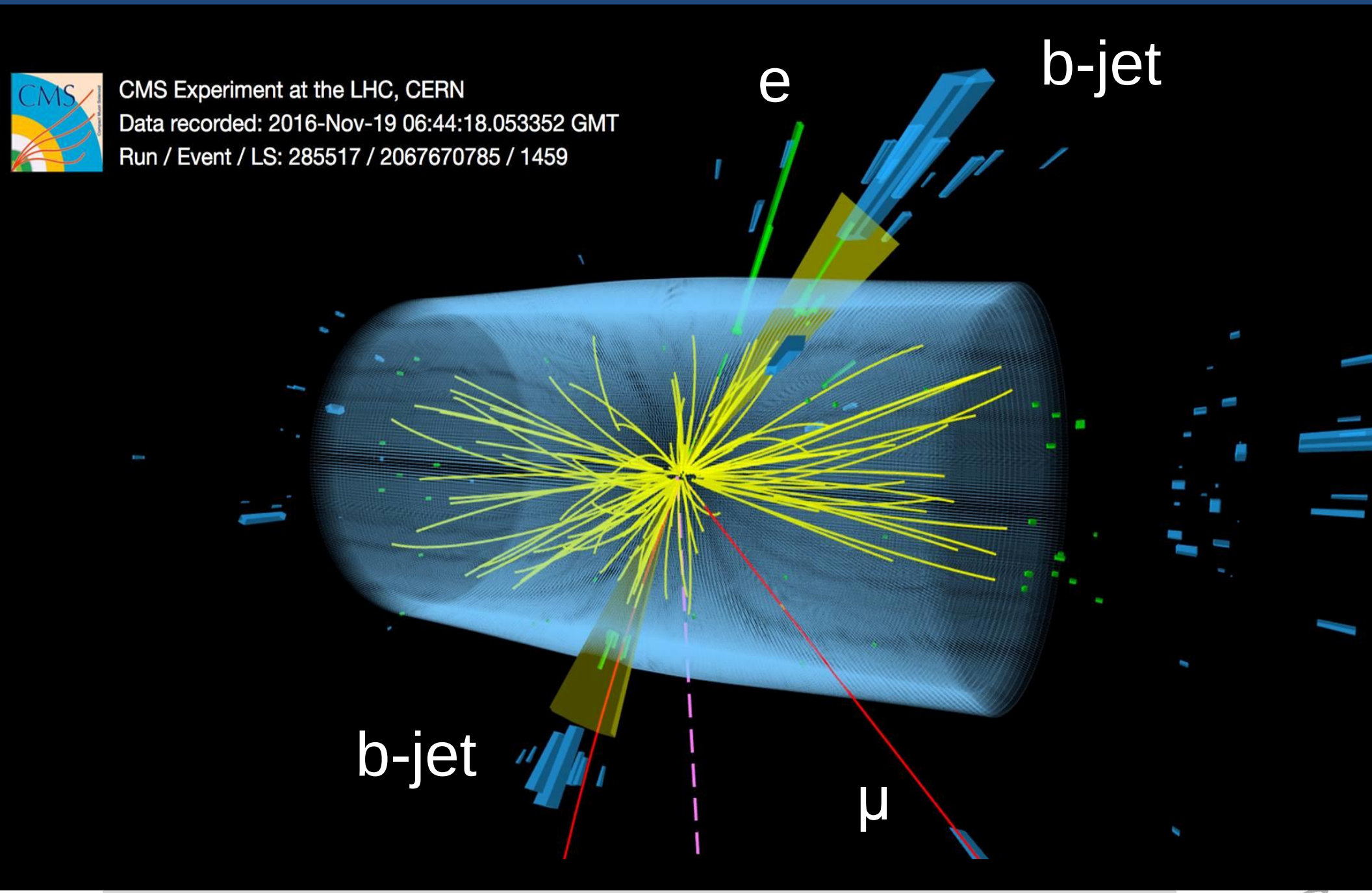
(Yen-Jie's gestimation)

Future Direction

- **Entered the era of precision measurement for open charm**
  - Explore open beauty measurements
  - Moving toward fully reconstructed D and B mesons which carry full info about the open heavy flavor hadron
  - Continue to improve the precision of spectra measurements and perform stress test on the models

- **Employ new experimental tools**
  - D-hadron and DDbar correlation
  - D v_2 – hadron v_2 correlation in engineered events
  - Jet-D correlation and fragmentation function

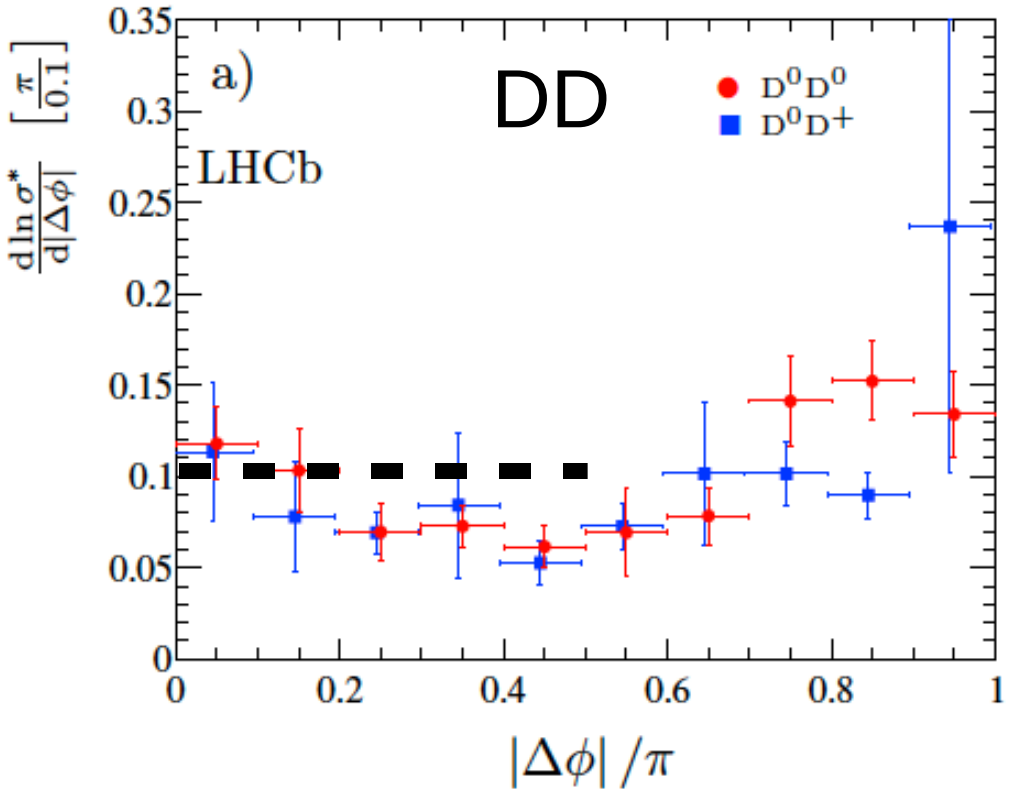
ttbar production in pPb collision

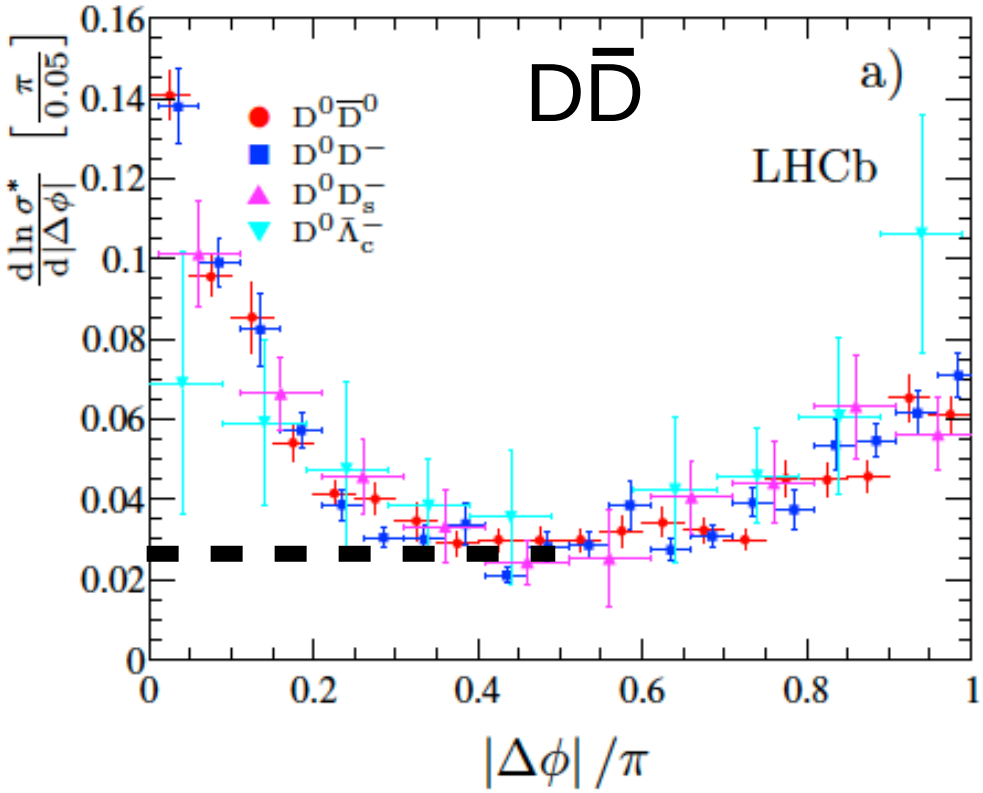


Backup slides

DD and DDbar correlations

DD and $D\bar{D}$ correlations measured by LHCb at 5.02 TeV

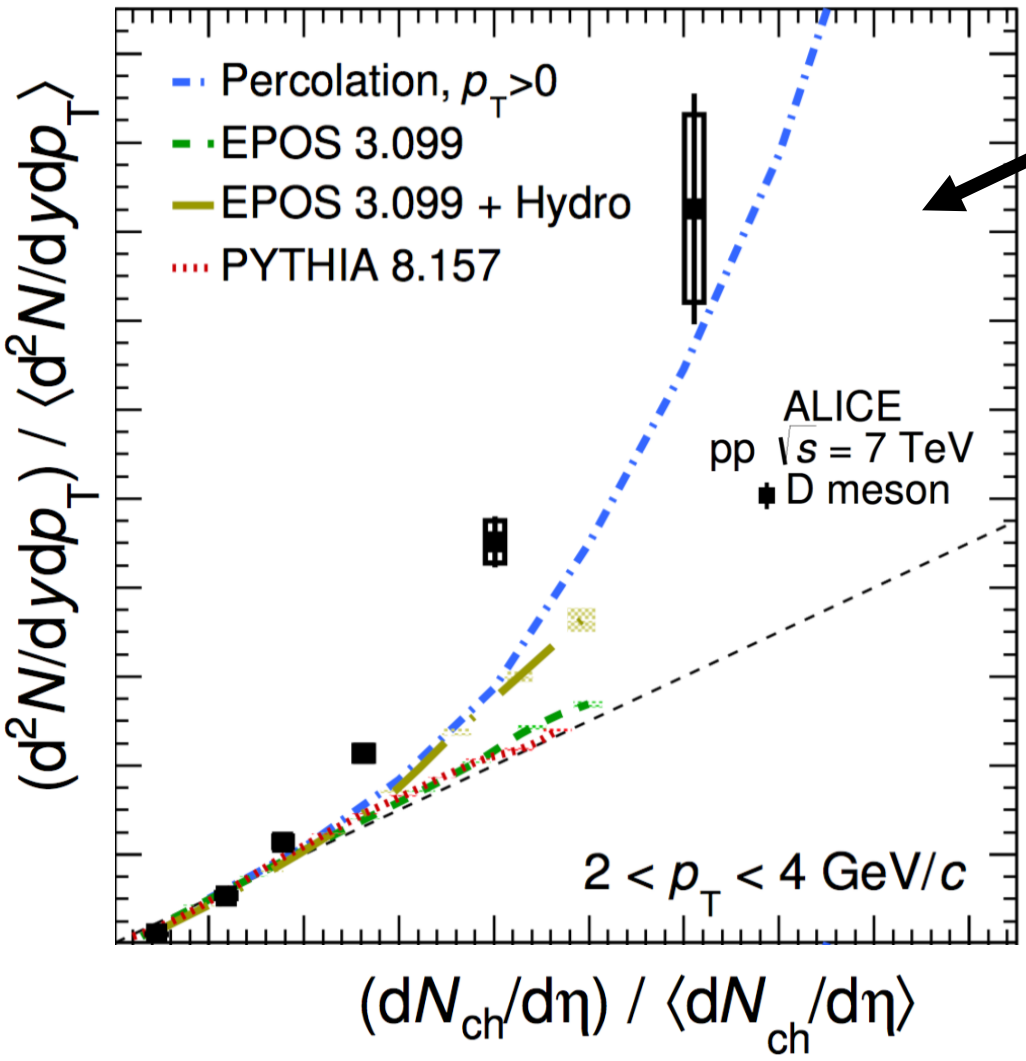




$D\bar{D}$ correlation show an enhancement with respect to DD correlation at low $\Delta\phi$ consistent with consistent contribution from gluon splitting

$c\bar{c}$ pairs produce by gluon splitting processes

HQ production as a function of multiplicity

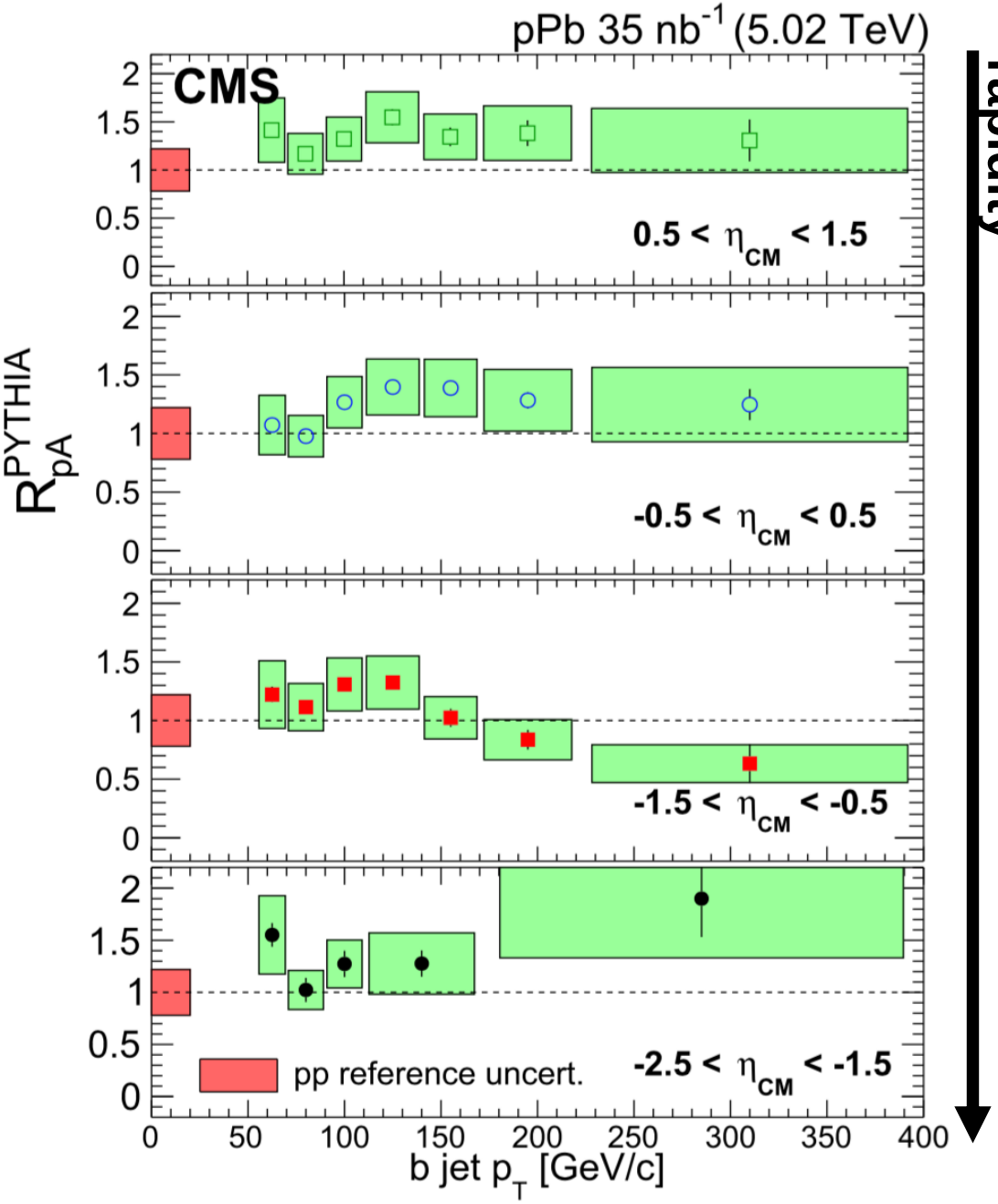


Strong dependence of D meson yield vs multiplicity

Need to include Multi-Particle-Interaction (MPI) to describe experimental data

ALICE data favours MPI models that includes a non linear dependence vs multiplicity (hydro?)

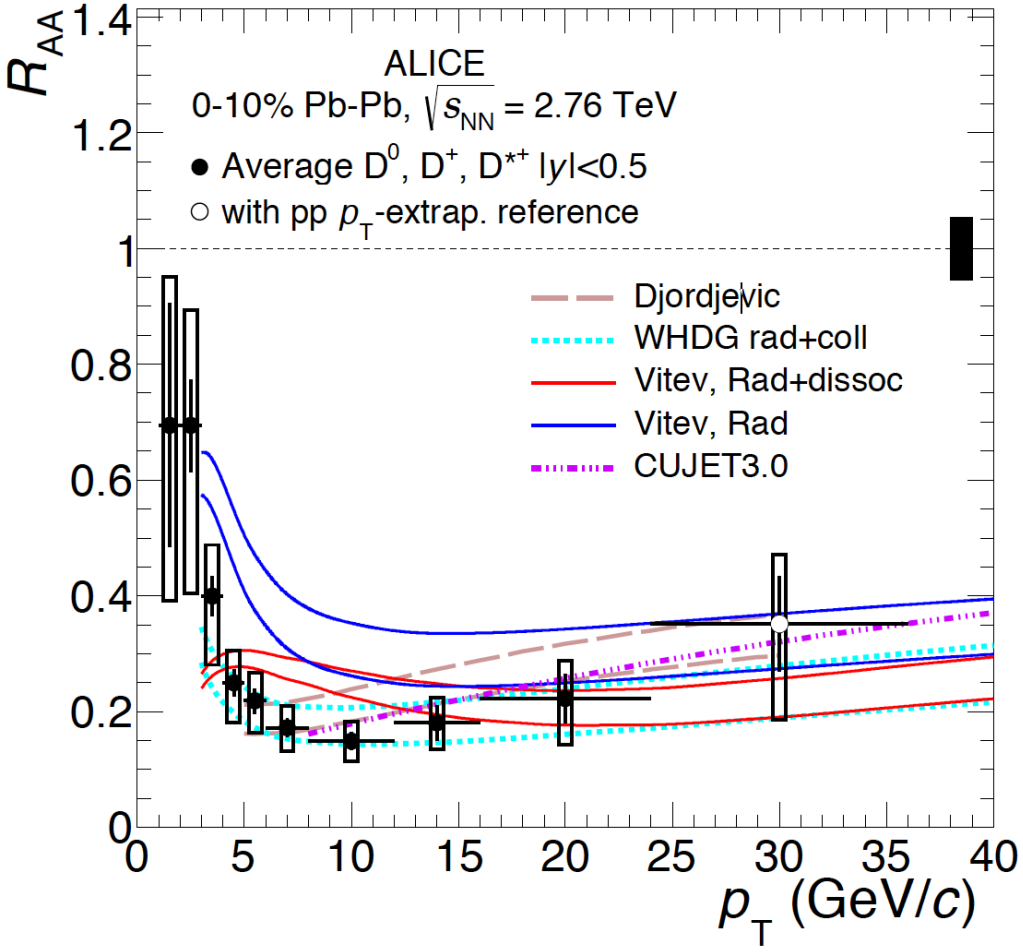
b-jet nuclear modification factor in pPb

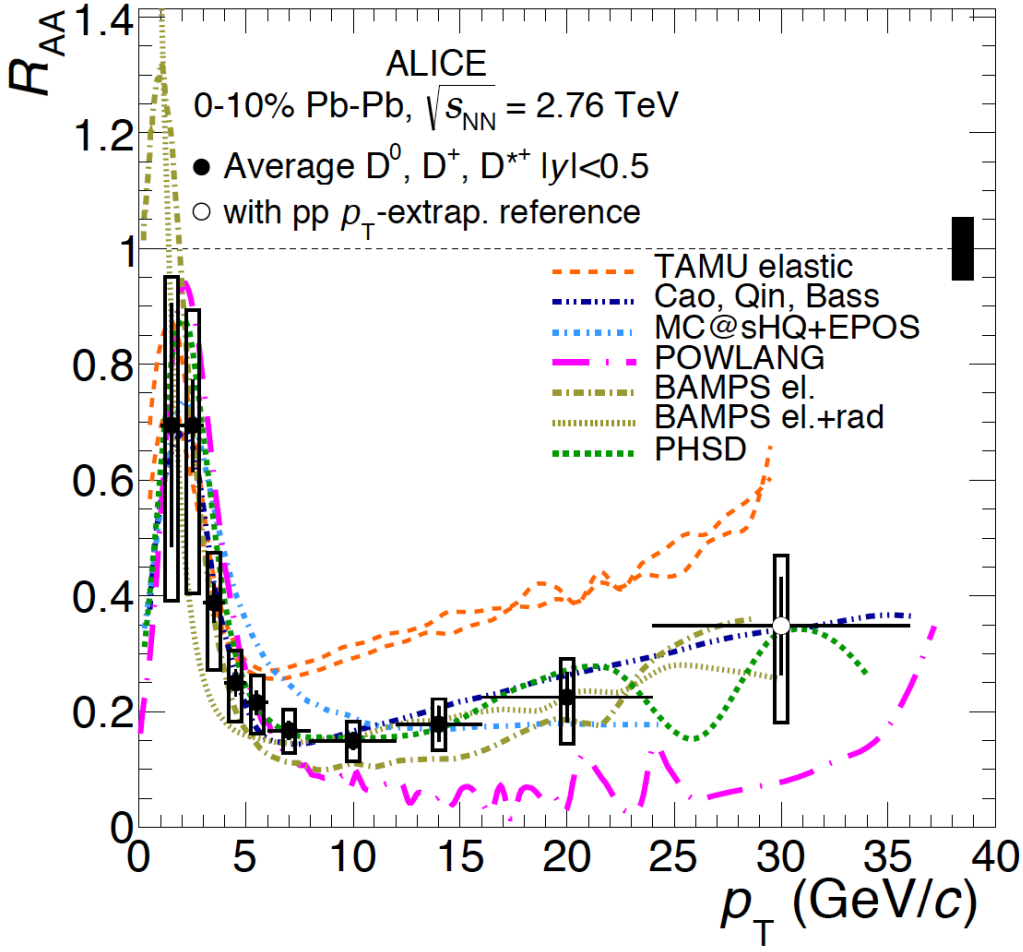


CMS b-jet R_{pA} in bins of transverse momentum and pseudo-rapidity

PYTHIA R_{pA} consistent with unity as a function of p_T and pseudo-rapidity

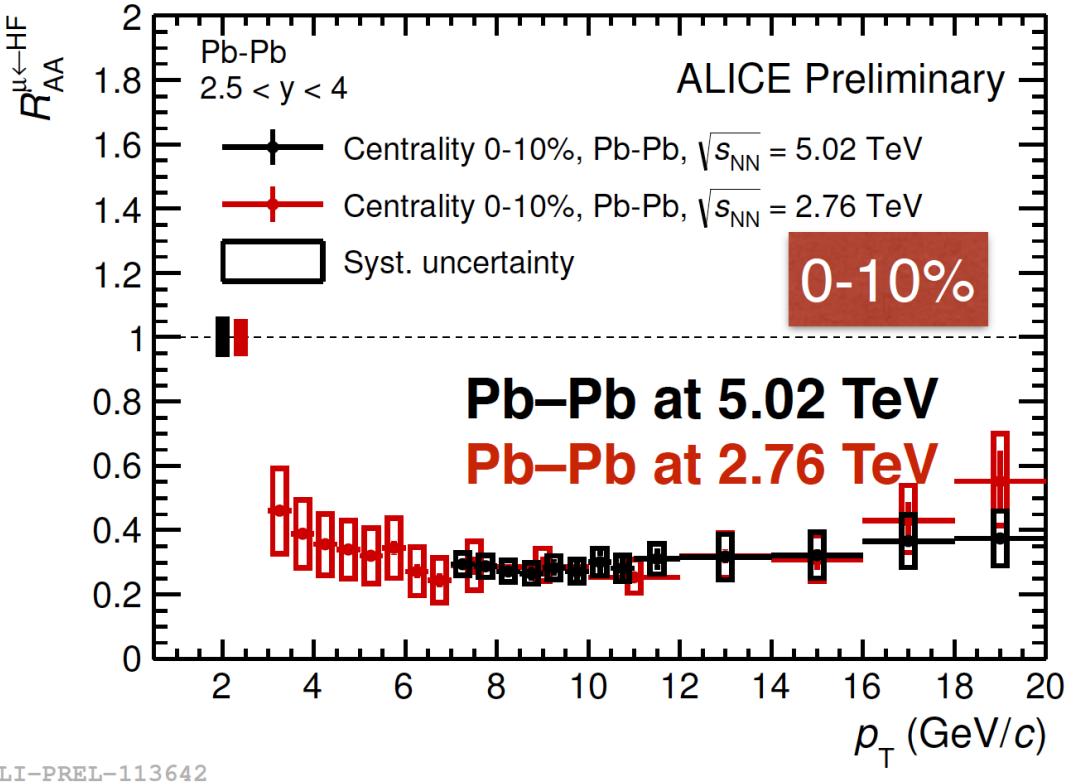
D meson RAA at 2.76 TeV





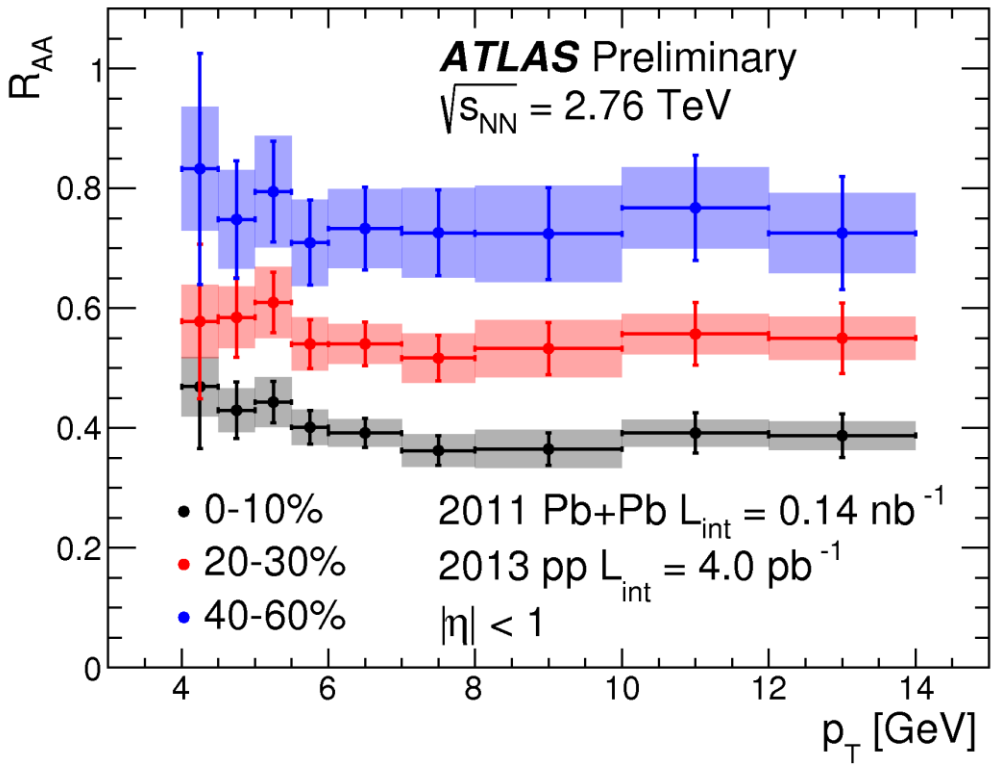
R_{AA} of heavy flavour muons

ALICE R_{AA} of heavy-flavour muons at 2.76 TeV and 5.02 TeV



LI-PREL-113642

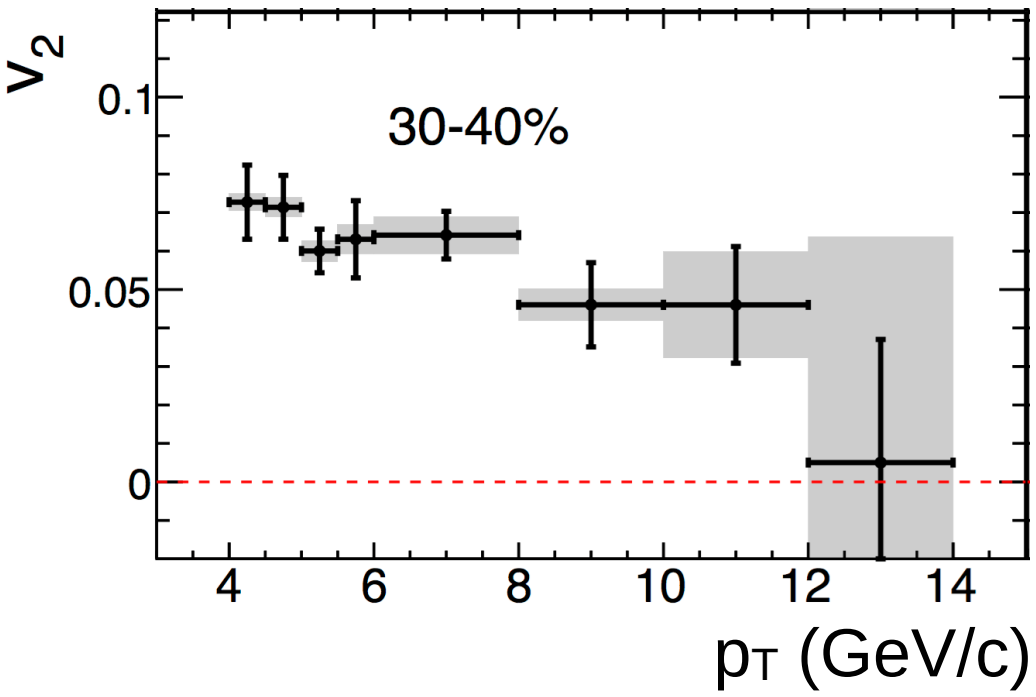
R_{AA} of heavy-flavour muons at 2.76 TeV from ATLAS

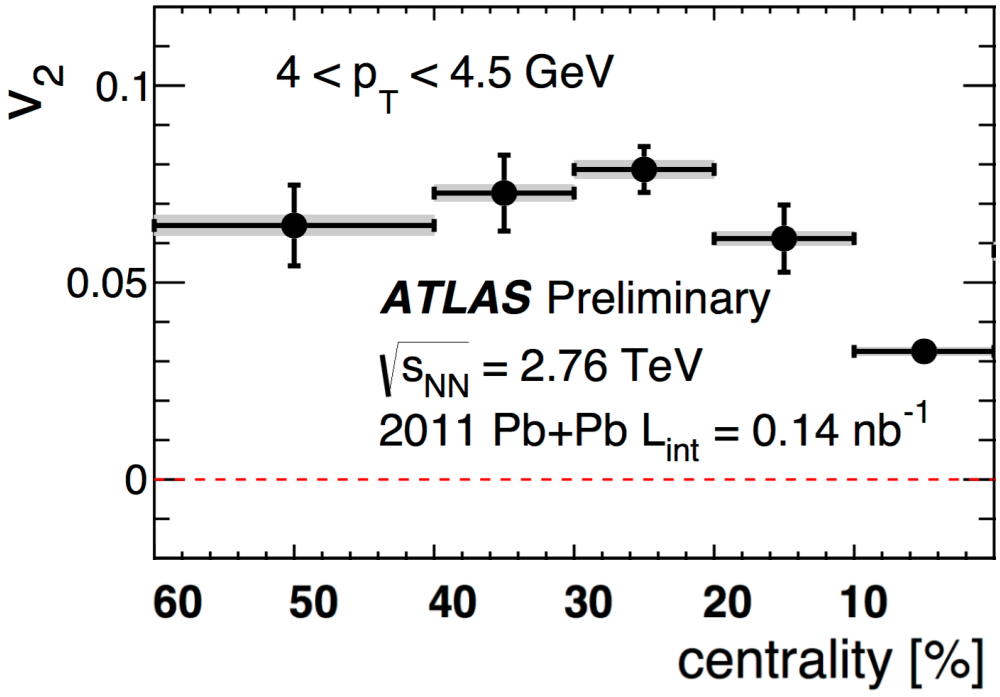


ATLAS-CONF-2015-053

- Precise measurement of HF muons at low p_T
  - *Same suppression observed at the two energies*
- Clear suppression pattern observed as a function of centrality

Heavy-flavour muons at 2.76 TeV





ATLAS-CONF-2015-053

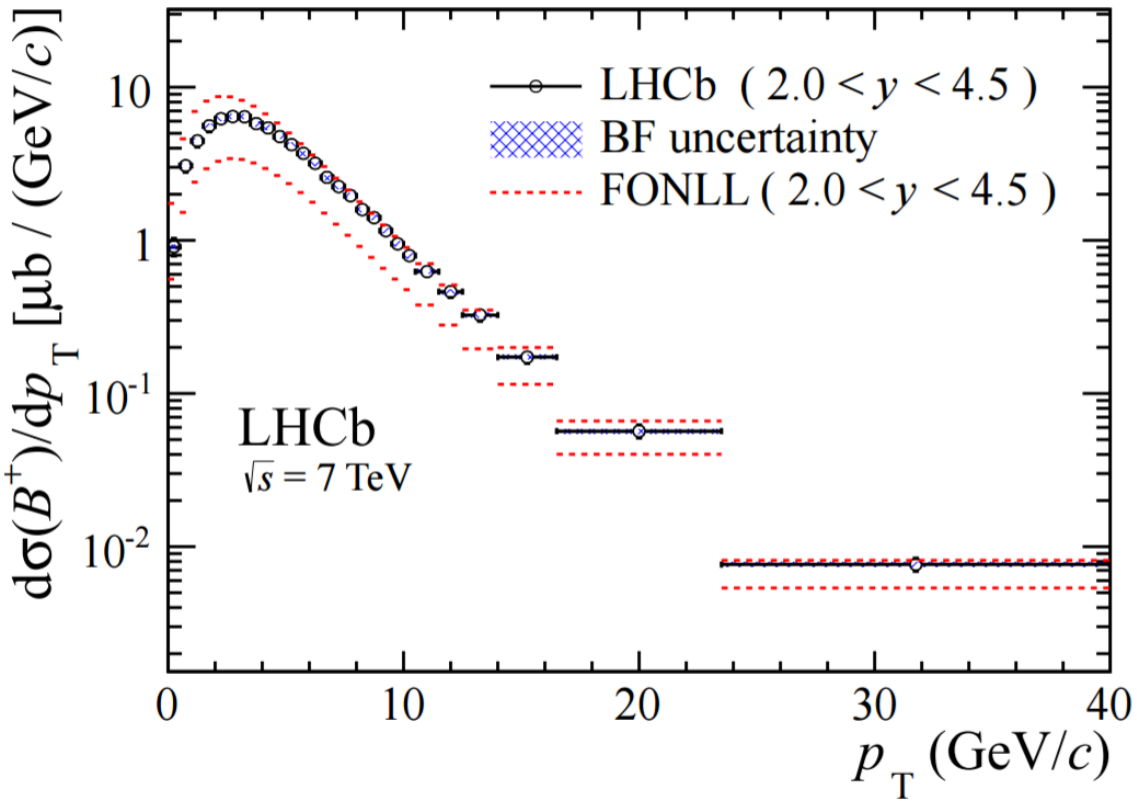
Positive v_2 for muons from heavy-flavour decays (b+c) at LHC:

- include the contributions of beauty to v_2 that is currently unknown
- **v_2 of heavy flavour muons < v_2 (D^0) from ALICE**

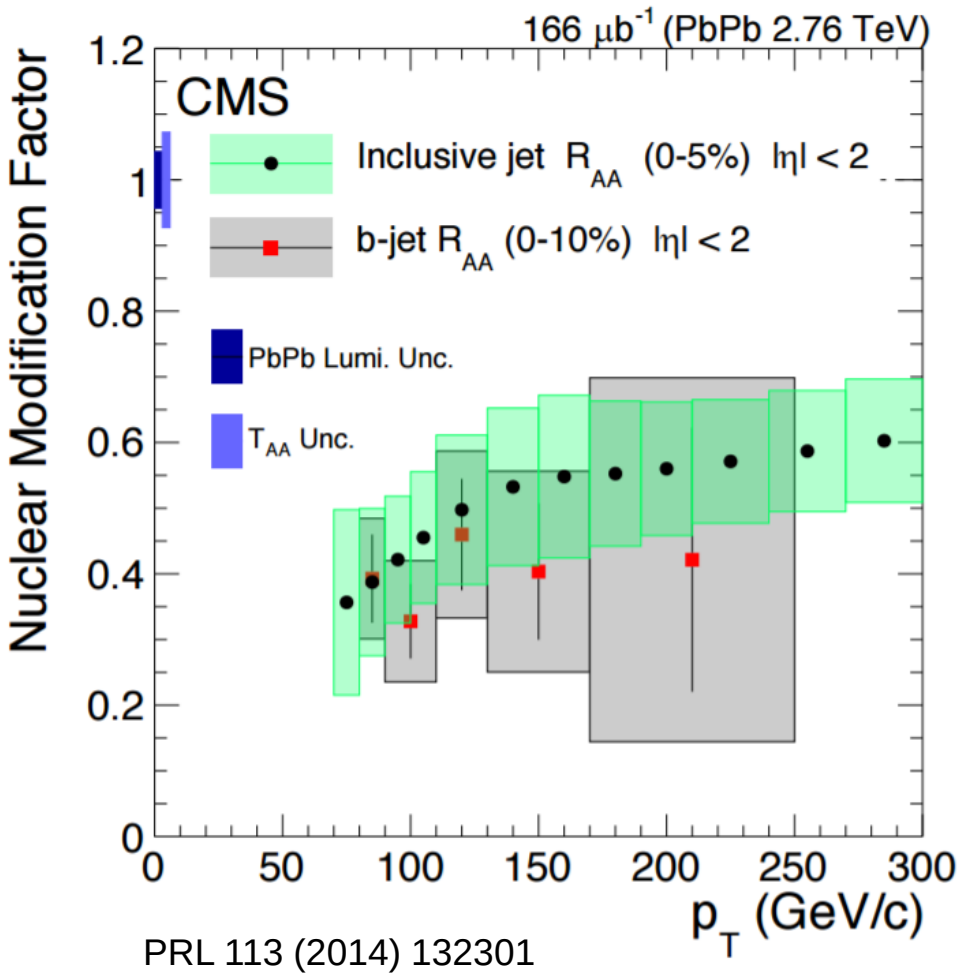
→ *indirect indication of $v_2(b)<v_2(c)$?*

B production at low p_T in pp

•**JHEP 1308 (2013) 117**



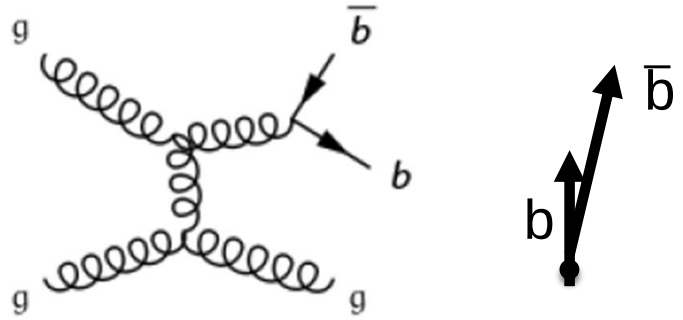
Flavor Dependence E_{loss} at Higher p_T



PRL 113 (2014) 132301

b-jet R_{AA}

inclusive jet R_{AA}



NLO process: Gluon splitting ~20%

→dominant at low opening angles

Same suppression for b-jets and inclusive jets at high p_T

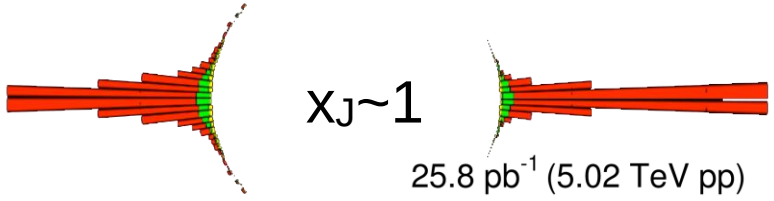
Mass difference negligible at high p_T

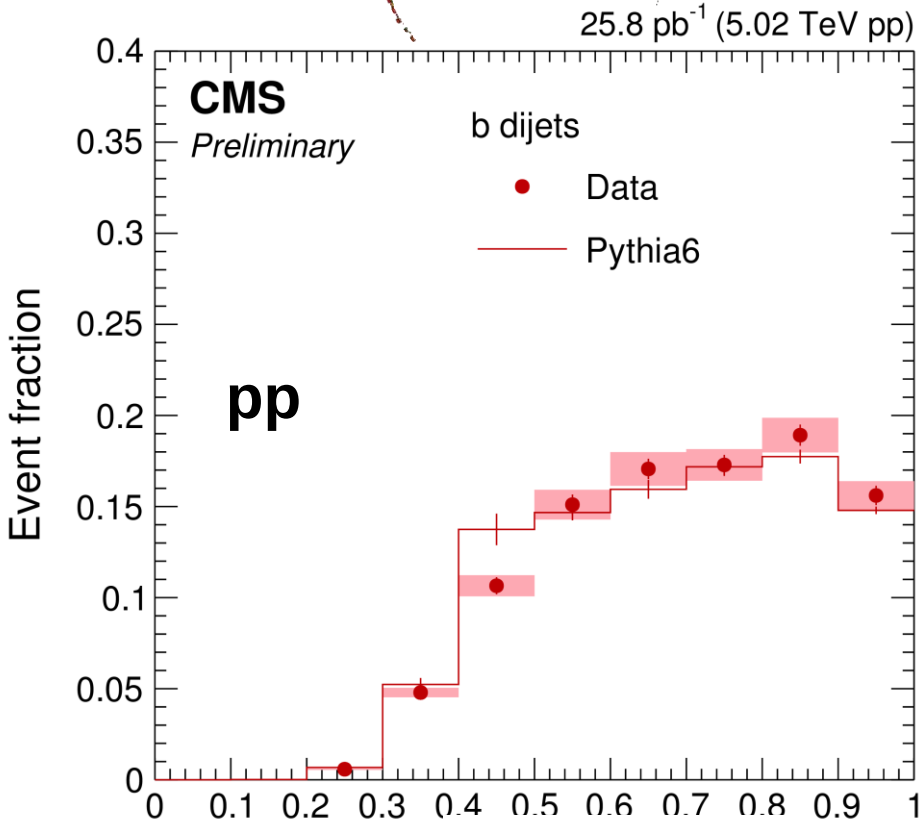
→***Large contribution of gluon splitting processes****? In GSP case, we are not measuring the b-quark E_{loss} but to some "fat" gluon E_{loss}*

B Dijet p_T Asymmetry

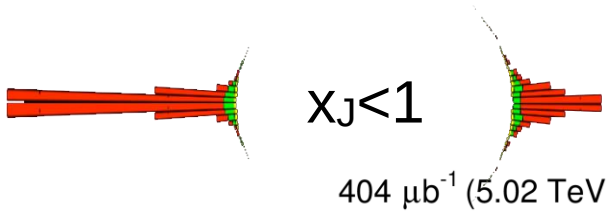
→ In back-to-back events $b\bar{b}$ production via gluon splitting processes is negligible

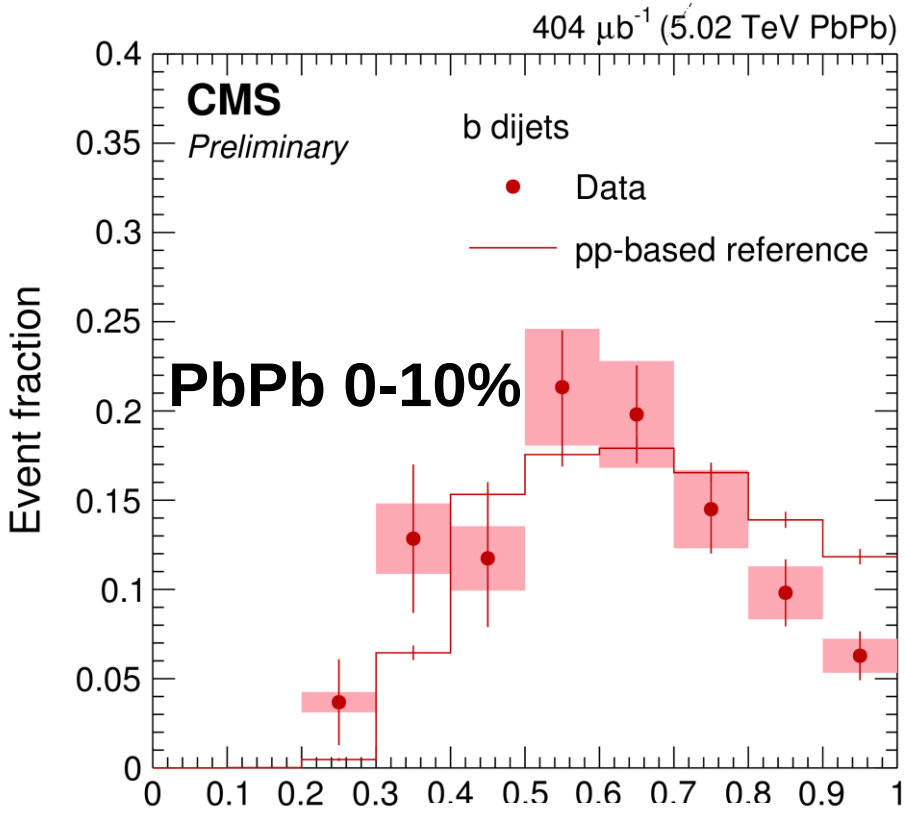
$p_{T,1} > p_{T,2}$





$x_J = p_{T,2} / p_{T,1}$



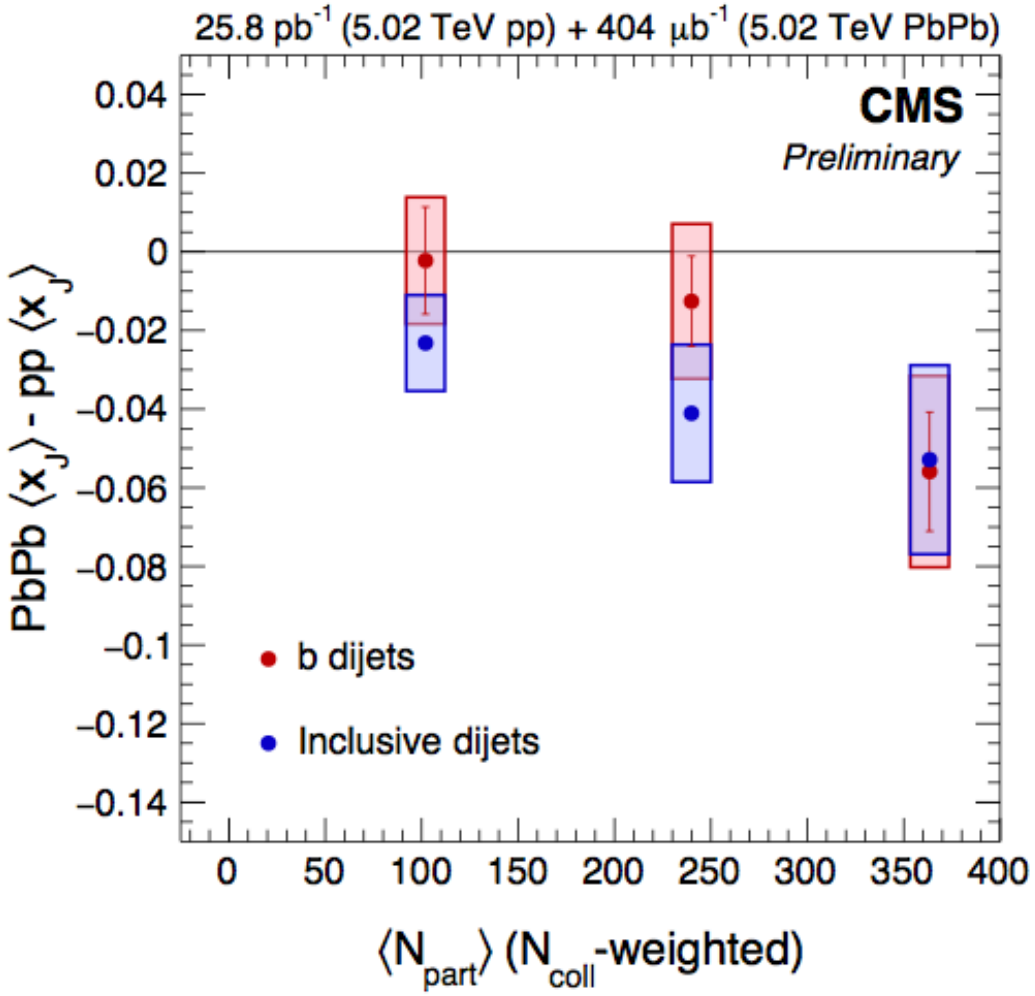


$x_J = p_{T,2} / p_{T,1}$

CMS-HIN-16-005

x_J distributions of b dijets significantly modified in central PbPb collisions!

B Dijets vs. Inclusive Dijets



$x_J = p_{T,2} / p_{T,1}$

Same average asymmetry observed for inclusive jets!

CMS-HIN-16-005

There is no significant difference in the suppression of inclusive and b-jets even after excluding the contribution of gluon splitting processes